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Effects of Moisture Content in Solid Waste Landfills

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AFIT/GEE/ENV/00M-03

EFFECTS OF MOISTURE CONTENT
IN SOLID WASTE LANDFILLS

THESIS

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THESIS

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Craig P. Eck

Table of Contents

List of Figures

Page

Page

List of Tables

Abstract

Solid waste landfills are an extremely complex and heterogeneous environment. Modeling the biodegradation processes within a landfill must involve an understanding of how environmental factors affect these processes. Arguably, the most important environmental factor influencing biodegradation processes is solid waste moisture content.

This thesis effort, which is an extension of a system dynamics model previously presented by Colborn (1997) and amended by Benter (1999), attempts to understand and model the effects of moisture content on waste degradation and landfill gas generation. The new moisture structure that was added to the previous models provides a better representation of the impact of moisture on aerobic and anaerobic hydrolysis and bacterial populations, and ultimately, gas generation. It also gives a clearer picture of how moisture is distributed between the solid waste and the void spaces within a landfill. Leachate and moisture infiltration flows were introduced into the model as a means to replicate the "wet-cell" or bioreactor landfill. Landfill managers could change the moisture parameters in the model to simulate the impact of different moisture configurations on waste degradation and methane generation. Transferring the information learned from the model to a real system could help optimize methane generation and accelerate landfill stabilization.

EFFECTS OF MOISTURE CONTENT IN SOLID WASTE LANDFILLS

I. Introduction

Background

The United States produces more municipal solid waste (MSW) per capita than any other nation. Despite the recent increase in recycling and reduction in MSW generation, 55% (116 million tons) of this waste is currently disposed of in landfills, and landfilling will remain the predominant method of MSW disposal well into the 21st Century.

Over the past 25 years, landfill construction and operation in the United States has drastically changed. Prior to the early 1970s, landfills were basically open pits where solid waste was dumped and either covered with a thin soil layer or burned (EPA, 1998: 119). There were no landfill liners or covers. Water was allowed to penetrate into and pass through the waste and leave in the form of leachate. Therefore, the waste was wet throughout and the waste decomposition and landfill gas generation processes were active (Lisk, 1991: 417). However, the departing leachate was allowed to contaminate the surrounding soil and ground water.

Since the mid-1970s, however, federal and state regulations and public resistance to siting have moved landfill construction and operation to the opposite extreme (Colborn, 1997: 30). The modern MSW landfill has evolved into a very sophisticated facility (Reinhart and Townsend, 1998: 1). All landfills are now constructed to have an impermeable liner and cover and also gas and leachate collection systems. This landfill approach is known as the "dry-tomb" philosophy. Moisture that is in the waste when buried remains in the landfill and is possibly removed by the leachate collection system. In addition, the runoff and precipitation outside the landfill are not allowed to enter. Therefore, the solid waste remains extremely dry. This dry environment minimizes the environmental impact of the landfill, but it is not conducive to waste biodegradation.

There is, however, another landfill philosophy that has been researched since the 1970s and is starting to gain acceptance by both the regulators and landfill operators. This "wet-cell" philosophy, which takes the benefits from both the "dry-cell" landfill and the water infiltrating "open-pit" landfill, treats landfills as solid waste bioreactors designed to enhance the microbial degradation of the waste. The "wet-cell", or bioreactor, landfill minimizes the environmental impacts from the solid waste by the use of an impermeable liner and cover and by gas and leachate collection systems. However, unlike the "dry-tomb" approach, water is allowed to infiltrate or is added to the solid waste, usually through leachate recycling, to increase its moisture content and enhance biodegradation. This enhanced biodegradation leads to increased landfill gas generation, specifically methane, which can provide economic benefits through energy recovery (Colborn, 1997: 4). In addition, increased biodegradation will reduce landfill stabilization time, therefore reducing the amount of time the liners must remain intact to prevent the leakage of leachate (Wall and Zeiss, 1995: 215).

To effectively manage and optimize the "wet-cell" landfill, the dynamic biodegradation processes associated with landfill operations must be adequately understood. Previous models of these processes have been developed using a system dynamics approach. In 1997, Captain Philip Colborn developed a system dynamics model to "explore the fundamental processes within the landfill biochemical reactor responsible for the degradation of municipal solid waste" (Colborn, 1997: 9). Colborn utilized gas generation as a metric for biodegradation and landfill performance. In 1999, Captain Brian Benter built upon and improved the model by further researching the availability of substrate to the microorganisms within the landfill during the hydrolysis phase of degradation (Benter, 1999: 51).

Problem Statement

The model constructed by Colborn and improved by Benter is an excellent system dynamics model of the fundamental biodegradation processes in a landfill. However, the model does not fully investigate the impact of moisture content on these processes and there are still some concerns about the modeling of the effect of moisture on the landfill, specifically "the location of moisture and its ability to be used by microorganisms" (Benter, 1999: 52).

Purpose Statement

The purpose of the thesis is to build upon the strengths of the Colborn and Benter models and to explore the effect of moisture content on the degradation processes within the "wet-cell" landfill. This improved version could serve as a solid foundation for a usable model that could be used in future landfill management to optimize landfill space and biodegradation.

Research Questions

1. How do landfill parameters and conditions affect solid waste moisture content?
2. How does moisture content and water movement affect the degradative processes within the "wet-cell" landfill?

3. How does moisture content and water movement affect landfill gas generation?

Scope/Limitations

Landfill gas concentration and flux will continue to be used as a metric of biodegradation and landfill performance. However, unlike the Colborn and Benter models, the scope and boundaries of this system dynamics model will be broadened to include the effects of moisture content and availability on degradation.

Modeling the degradation processes within a landfill can be complex because of its heterogeneous nature. Landfills, and even sections within the same landfill, are extremely diverse. However, by using the existing system dynamics model and available literature, and by focusing on the research questions, new insight and knowledge will be advanced about landfill biodegradation processes.

II. Literature Review

Landfill Biodegradation Processes

Landfill biodegradation proceeds according to physical, chemical, and biological processes. The most significant of these three functions controlling degradation are the biological processes (Murphy and Brennan, 1992: 2). When solid waste is placed in a landfill, the biodegradation of the waste proceeds in several phases and, depending on biotic and abiotic conditions, can take less than one year or more than fifty years to complete.

This biodegradation process is usually explained as a four- or five phase time sequence which uses landfill gas generation as the metric to distinguish between phases. The four-phase sequence is broken up into an aerobic phase, an anaerobic acid phase, an accelerated methane production phase, and a decelerated methane production phase (Palmisano and Barlaz, 1996: 39-45). The five-phase sequence breaks the anaerobic acid phase from the four-phase model into two phases, transition and acid. The five-phase sequence proceeds along the following phases: initial adjustment (I), transition (II), acid (III), methane fermentation (IV), and maturation (V) (Tchobanoglous and others, 1993: 384-387). Figure 1 combines and illustrates both the four-phase (empirical) and five-phase (theoretical) sequences. Table 1 describes the processes and degradative steps taking place in each phase.

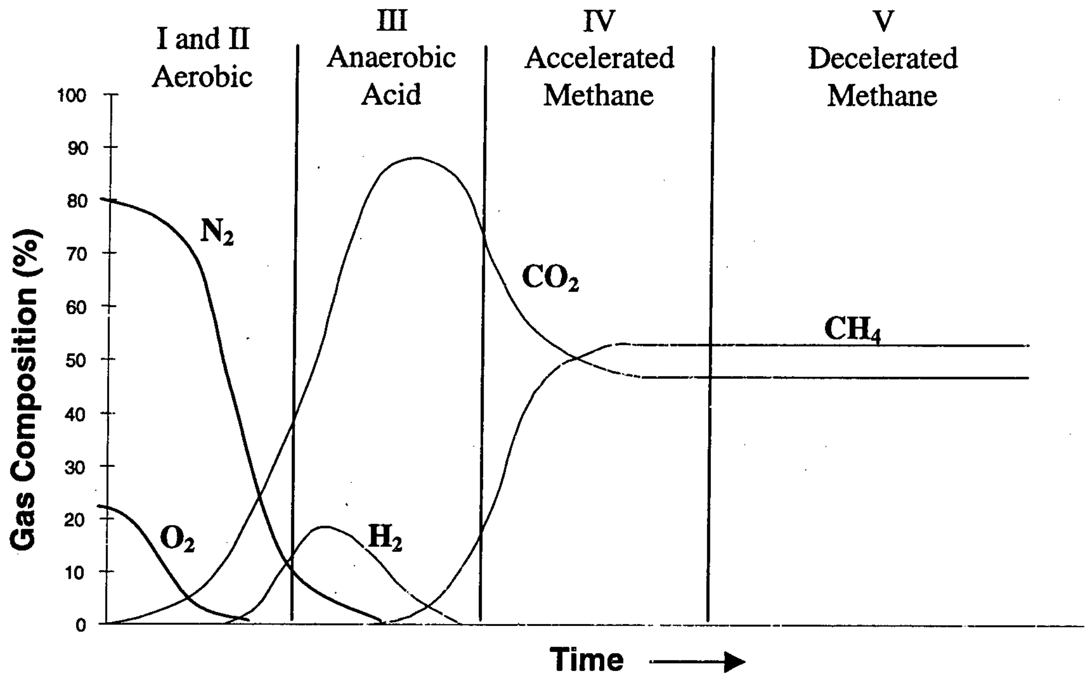


Figure 1. Generalized Phases of Landfill Gas Generation during Decomposition (after Tchobanoglous and others, 1993: 385; Palmisano and Barlaz, 1996: 40)

Table 1. Summary of Landfill Gas Generation Phases and Degradative Steps (after Colborn, 1997: 14-20)

Four-Phase	Five-Phase	Phase Description	Degradative Steps
Aerobic	Initial Adjustment	Beginning of decomposition under aerobic conditions; O_2 depleted; CO_2 produced (3-10 days).	Aerobic Degradation
---	Transition	O_2 completely depleted; anaerobic decomposition begins.	Begin Hydrolysis, Begin Fermentation
Anaerobic Acid	Acid	Anaerobic decomposition; organic acids accumulate; CO_2 principal gas generated; H_2 also produced; pH decreases (10-50 days).	Hydrolysis, Fermentation, Begin Acetogenesis and Methanogenesis
Accelerated Methane	Methane Fermentation	Rapid accumulation of methane; CO_2 also produced; organic acids consumed; pH increases (90 days to several years).	Hydrolysis, Fermentation, Acetogenesis, Methanogenesis
Decelerated Methane	Maturation	Production of methane remains steady until organic matter is depleted (90 days to several years).	Reduced Hydrolysis, Fermentation, Acetogenesis, and Methanogenesis

Biodegradation of solid waste, regardless of whether it is broken down into four or five phases, can be classified into two types of biological transformations, aerobic and anaerobic.

Aerobic Transformation. The generic aerobic transformation of solid waste can be explained by the following equation (Tchobanoglous and others, 1993: 677):

$$\text{Organic matter} + O_2 + \text{Nutrients} \xrightarrow{\text{Bacteria}} \text{New cells} + \text{Resistant organic matter} + CO_2 + H_2O + NH_3 + SO_4^{2-} + \ldots + \text{Heat}$$

When solid waste is buried in a landfill, atmospheric air, composed of mostly nitrogen and oxygen, is trapped in the void spaces (Palmisano and Barlaz, 1996: 41). As is shown in Figure 1, this air is approximately 80 percent nitrogen and 20 percent oxygen. During aerobic transformation, this oxygen, plus oxygen dissolved in the solid waste moisture, supports both aerobic hydrolysis and aerobic degradation. The oxygen is consumed, with soluble sugars serving as the carbon source for microbial activity. At the completion of the aerobic phase, the landfill gas will be composed of nearly 100 percent CO_2 (Palmisano and Barlaz, 1996: 41). The aerobic phase is normally completed in less than two weeks (Lisk, 1991: 424).

Anaerobic Transformation. The generic anaerobic transformation of solid waste can be explained by the following equation (Tchobanoglous and others, 1993: 681):

$$\text{Organic matter} + H_2O + \text{Nutrients} \xrightarrow{\text{Bacteria}} \text{New cells} + \text{Resistant organic matter} + CO_2 + CH_4 + NH_3 + H_2S + \text{Heat}$$

The biological conversion of the organic fraction of the solid waste during anaerobic transformation is thought to occur in three steps: hydrolysis (including fermentation), acetogenesis, and methanogenesis. Figure 2 illustrates these anaerobic degradation processes.

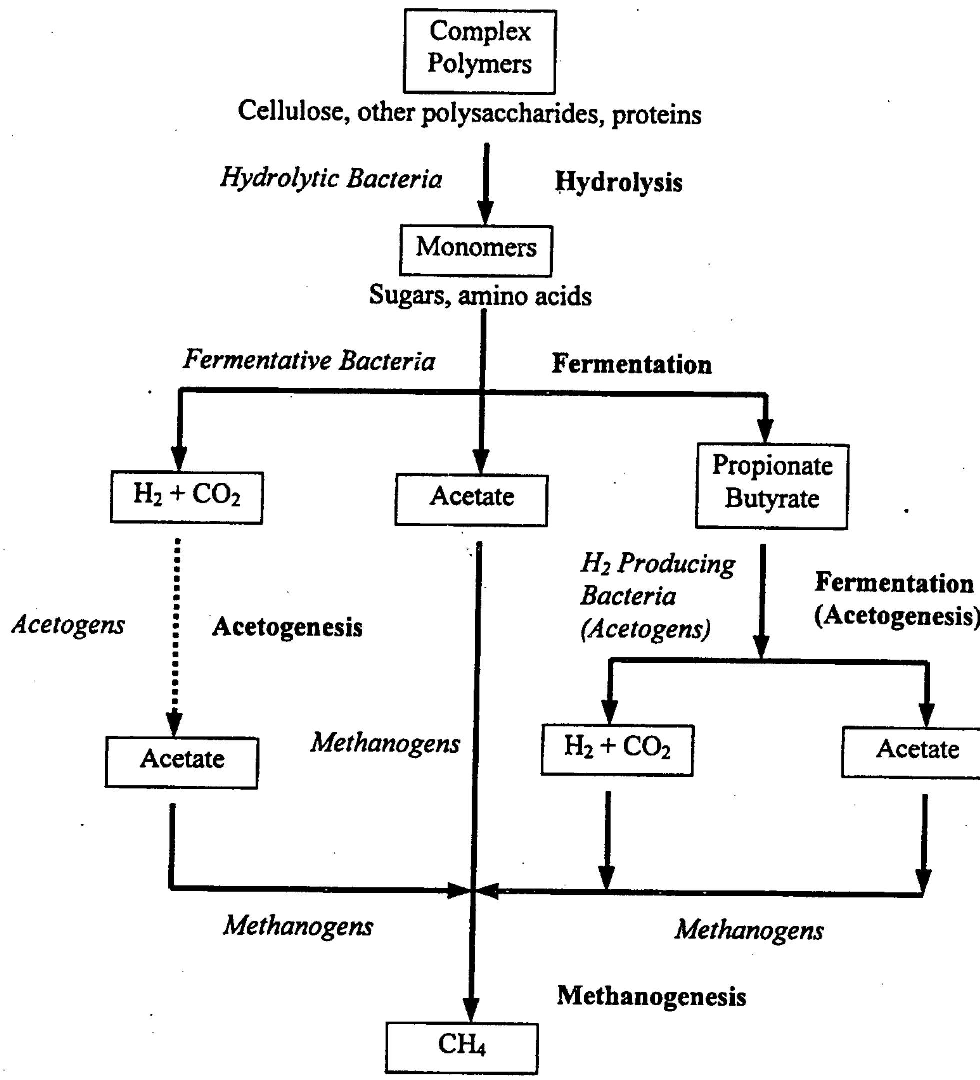


Figure 2. Anaerobic Degradation by Consortia of Anaerobic Bacteria (Palmisano and Barlaz, 1996: 38).

Hydrolysis. The first anaerobic reaction, a two step process that begins after the depletion of oxygen, is the hydrolysis of polymers such as carbohydrates, fats, and proteins. The initial products of polymer hydrolysis are soluble sugars, amino acids, and long-chain carboxylic acids. Fermentative microorganisms then ferment these hydrolysis products to short-chain carboxylic acids, ammonia, carbon dioxide, and hydrogen. Acetate and alcohol are also formed (Barlaz, 1997: 542). Hydrolysis is characterized by a rapid accumulation of carboxylic acids and a decrease in pH to below 6.0. The decrease in pH is due to the accumulation of acidic intermediates of sugar fermentation which results from the low acid-consuming activities of the acetogenic and methanogenic bacteria populations (Palmisano and Barlaz, 1996: 41-42).

<u>Acetogenesis</u>. Acetogenesis is carried out by obligate proton-reducing (or H_2-producing) acetogens. These acetogens oxidize fermentation products, including propionate and butyrate, to acetate, carbon dioxide, and hydrogen. Oxidation of propionate and butyrate is thermodynamically favorable only at very low hydrogen concentrations. Therefore, for acetogenesis to effectively proceed, the methanogenic bacteria must be sufficiently scavenging the available hydrogen (Barlaz, 1997: 542).

<u>Methanogenesis</u>. Methanogenesis is the final step in the transformation of complex polymers to methane. The methanogenic bacteria carry it out and the most common methanogenic substrates are acetate and hydrogen plus carbon dioxide (Barlaz, 1997: 543). The consumption of acetate during methanogenesis allows for an increase in pH (Palmisano and Barlaz, 1996: 43).

<u>Colborn Model</u>

In 1997, Captain Philip Colborn constructed a system dynamics model that simulated the progression of biodegradation and established an appropriate boundary for including the requisite entities needed to model the fundamental processes of landfill biodegradation. Also, it captured the interrelationships and feedback loops within and between degradative steps (Colborn, 1997: 139).

System Dynamics. System dynamics modeling is a method of dealing with questions about the dynamic tendencies of complex systems. In other words, it investigates the behavior patterns that systems generate over time. System dynamics is generally unconcerned with precise numerical values of system variables and is more concerned with general system dynamic tendencies and behavior (Meadows, 1980: 31). System dynamics mechanistically reproduces system behavior by identifying and modeling the underlying fundamental processes driving basic system behavior (Moorhead and others, 1996: 137). Modeling these processes allows for the study of internal interactions of complex systems and it provides a better understanding of the impact of various parameters on the dynamic interrelationships of the system. Modeling also allows for the investigation of system behavior outside the range of actual system observation (Shelley, 1999).

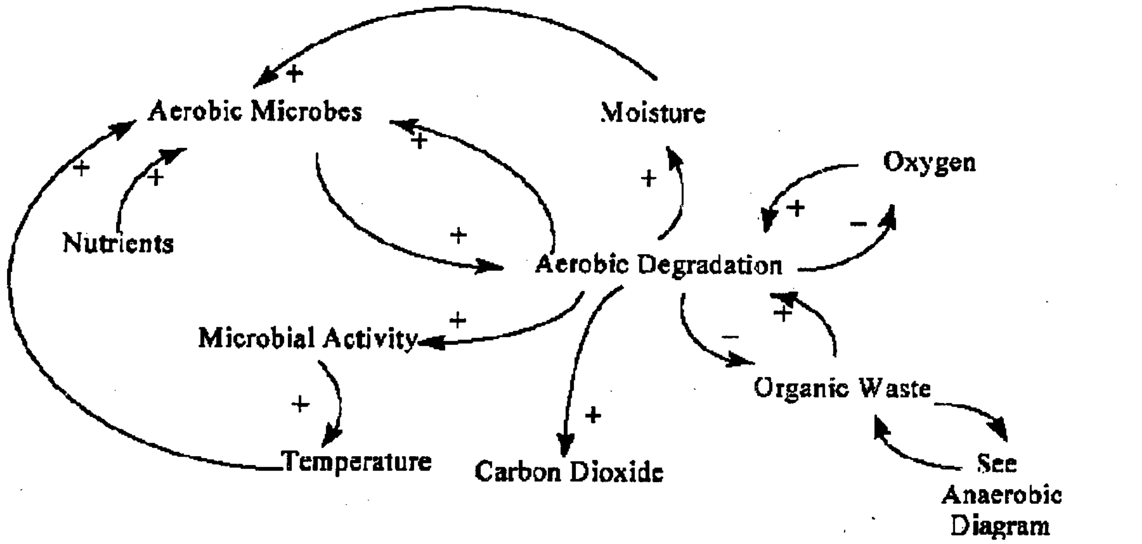
The modeling process is usually broken down into four stages: conceptualization, formulation, testing, and implementation. The conceptualization stage consist of studying the general problem area through a literature review and discussion with experts in the field, defining the question to be addressed, and describing the time development of interest and basic mechanisms by deriving a reference mode and an influence diagram. Formulation consists of constructing a flow diagram and then a system dynamics model based on the conceptualization of the system. The testing stage verifies that the model is performing as intended from the conceptual model and it validates whether the conceptual model is an accurate representation of the system under study. After the testing stage has built confidence in the model, the model can be implemented and used in the field to study system behavior (Shelley, 1999).

Conceptualization

Reference Mode. A reference mode is the expected development or behavior of a system over a time period of interest. It can be derived from historical data or theoretically by consulting relevant literature and experts in that specific field of study (Shelley, 1999). Colborn used a modified version of the four- and five-phase diagram of landfill gas generation as his reference mode (see Figure 13 in Chapter 4).

Influence Diagram. An influence diagram explicitly lays out the cause-and-effect structure suggested by the reference mode (Shelley, 1999). It is also constructed using relevant literature. Colborn's influence diagram incorporates the cause-and-effect relationships between the important entities that best represent the biodegradation process (Colborn, 1997: 46). The influence diagram constructed by Colborn is shown in Figure 3. A positive (+) sign denotes a positive interaction and a negative (-) sign denotes a negative interaction between the entities.

Formulation. The influence diagram is used to formulate a flow diagram. A flow diagram translates notional influence structure to a real operating system representation which complies with the logic represented in the influence diagram (Shelley, 1999). The generic biodegradation and gas generation flow diagram developed by Colborn is illustrated in Figure 4. Colborn then used the flow diagram and initial system parameters to construct his system dynamics model using STELLA computer modeling software. STELLA is a software package that allows for flow diagram construction in a model building process (Colborn, 1997: 49).



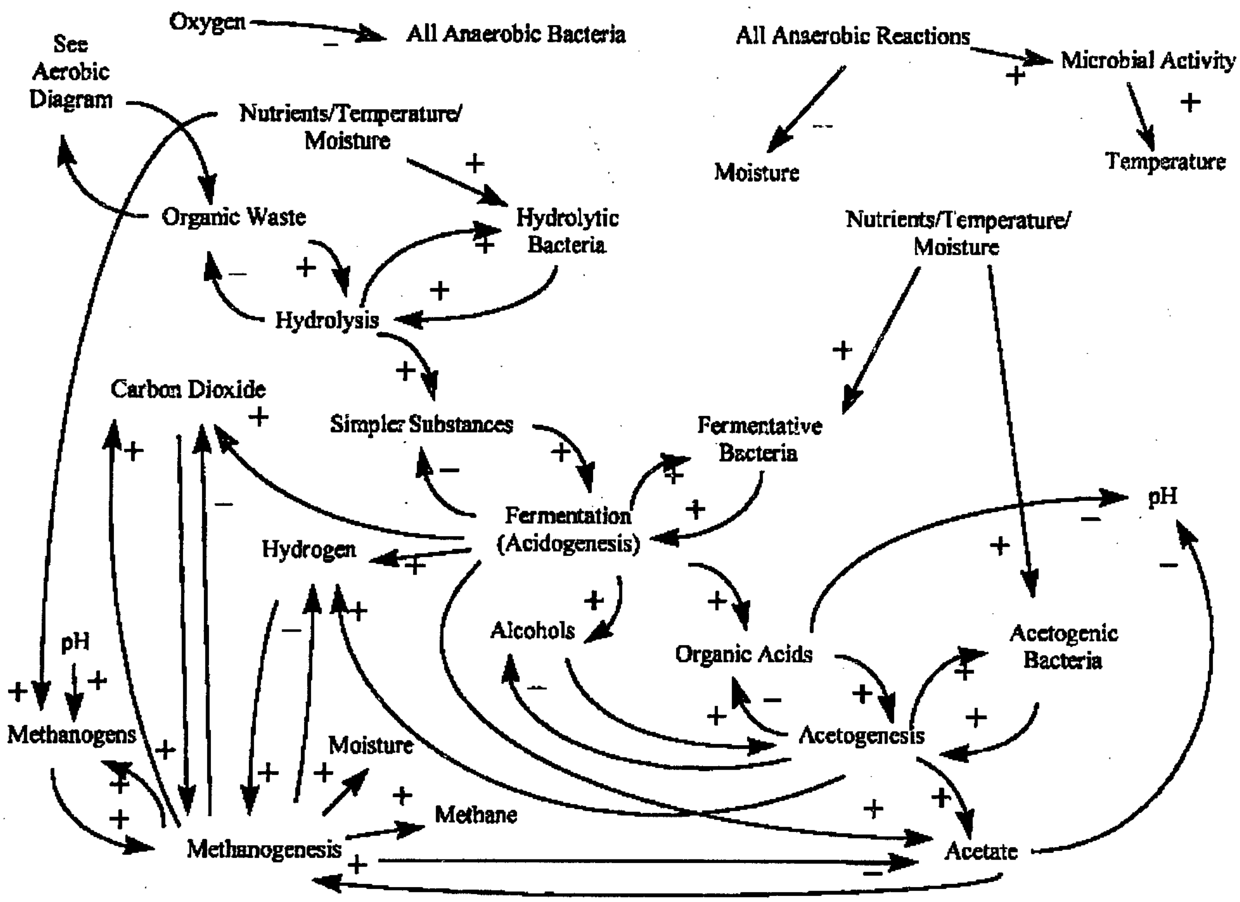


Figure 3. Colborn Model Influence Diagram (Colborn, 1997: 57-58)

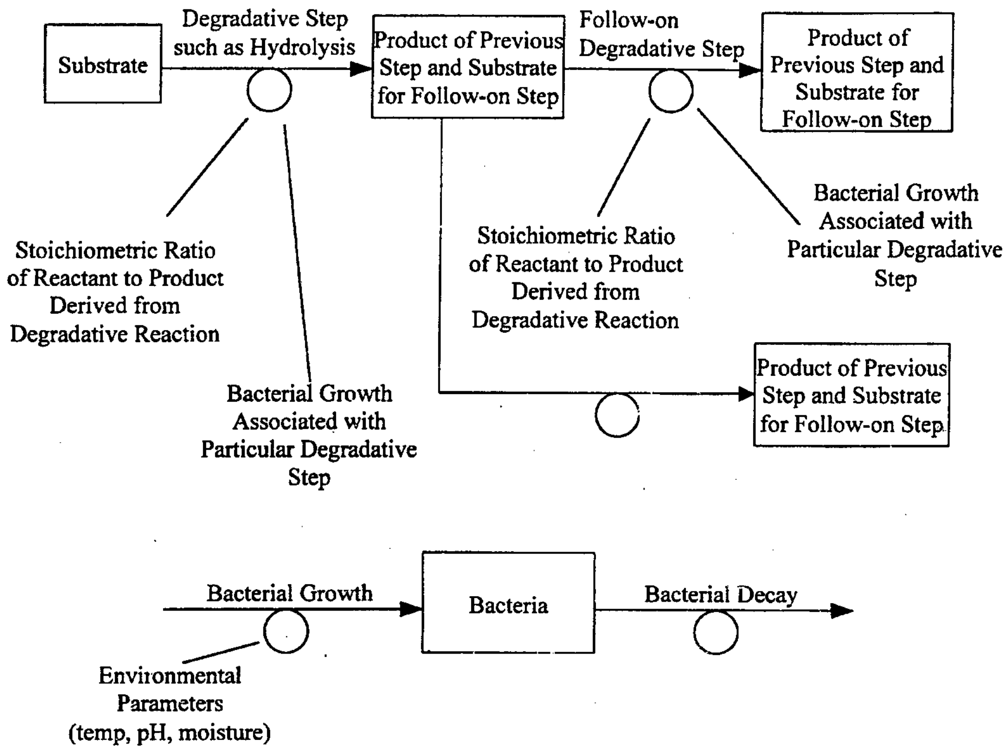


Figure 4. Generic Flow Diagram from the Colborn Model (Colborn, 1997: 60)

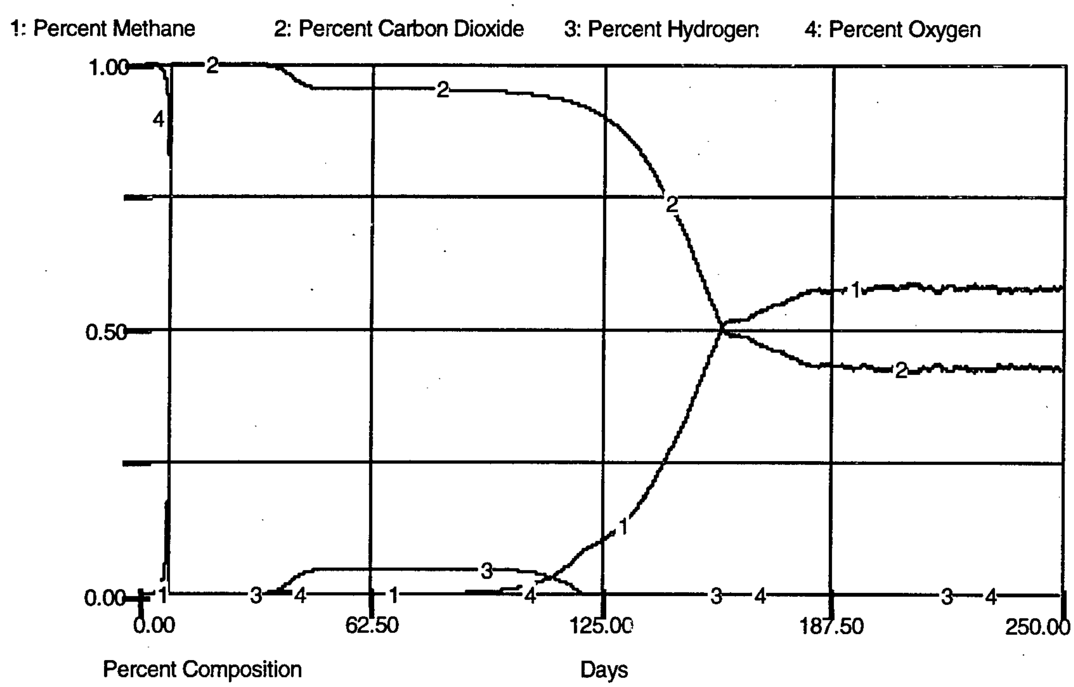


Figure 5. Basic Output of Colborn Model (Colborn, 1997: 66)

Testing. Using the STELLA model constructed during the formulation phase, Colborn tested and validated his model for comparison against the reference mode. Figure 5 is the basic output of the Colborn model. Comparing this output to the reference mode yields an adequate match. Colborn also used several methods of verification to test his model. Throughout the testing and verification, the model performed satisfactorily.

However, despite the satisfactory testing and increase in confidence, Colborn's model did have some weaknesses that needed to be studied further. One of these weaknesses, the mechanism associated with substrate availability during hydrolysis, was investigated in Captain Brian Benter's thesis in 1999. Another weakness in the Colborn model is the limited modeling of the effects of moisture content on bacterial growth and system behavior. Colborn states that the model behavior is most sensitive to the parameter of moisture content. Despite this important impact on behavior, moisture is not adequately studied and is only generically modeled into bacterial growth (Colborn, 1997: 139).

Benter Model

In 1999, Captain Brian Benter researched the dynamics of substrate availability in sanitary landfills during hydrolysis (Benter, 1999: 5). This area was not effectively depicted in the Colborn model. Benter addressed this problem by changing hydrolytic microbial growth from Monod kinetics, which was used to model all microbial growth in the Colborn model, to growth based on the surface area of the substrate. The surface area represents the population of microorganisms present around a sphere of organic waste (Benter, 1999: 30). This change provided a different, and probably better, representation of what happens as solid organic waste is transformed to simpler substances. Benter then incorporated this change into the existing Colborn model "in an attempt to more accurately simulate the processes of microbial degradation in a sanitary landfill" (Benter, 1999: 5).

Reference Mode. Benter used the same reference mode as Colborn. This reference mode is illustrated in Figure 12 in Chapter 4

Influence Diagram. Benter used the same influence diagram as Colborn with one exception. Benter expanded upon the Hydrolysis section of the diagram. Figure 6 shows the hydrolysis influence diagram that Benter constructed and used to replace the hydrolysis section of the Colborn influence diagram.

Formulation. Using the new influence diagram, Benter amended Colborn's flow diagram. The flow diagram is very similar except that the hydrolysis degradative step is separated from the other degradative steps to more accurately represent the process of hydrolysis. Figure 7 shows the hydrolysis step that was added to the flow diagram. This change was then incorporated into the STELLA model.

Testing. After modifying the Colborn model, Benter ran numerous simulations to compare the output to the reference mode. Figure 8 shows the basic output of the Benter model. "The revised model reflects the reference mode and is an improvement over the previous model" (Benter, 1999: 33). The Benter model also performed satisfactorily in the verification phase.

The Benter model improved the Colborn model and it presented a more accurate picture of not only the hydrolysis process but also the entire degradation process (Benter, 1999: 51). However, as with the Colborn model, the Benter model does have some

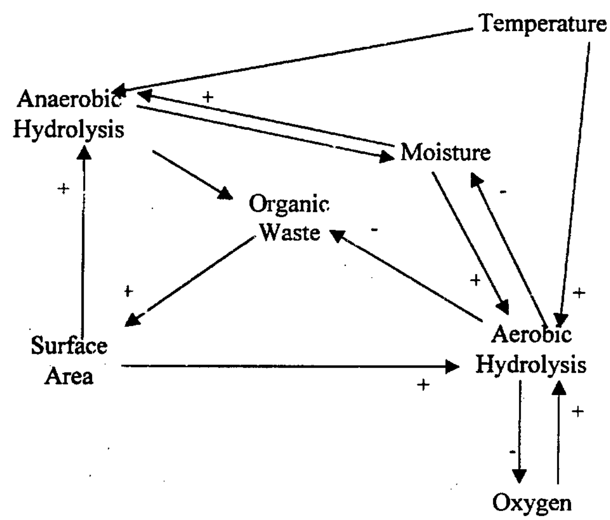


Figure 6. Benter Hydrolysis Influence Diagram (Benter, 1999: 29)

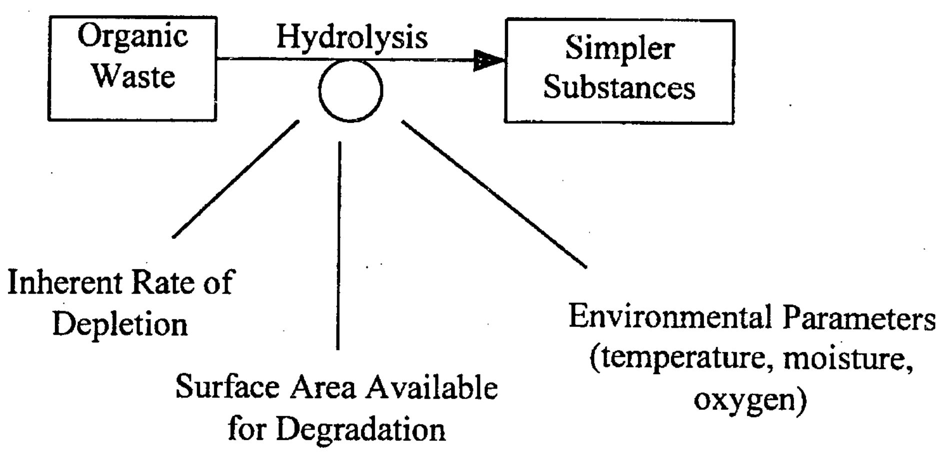


Figure 7. Benter Hydrolysis Flow Diagram (Benter, 1999: 31)

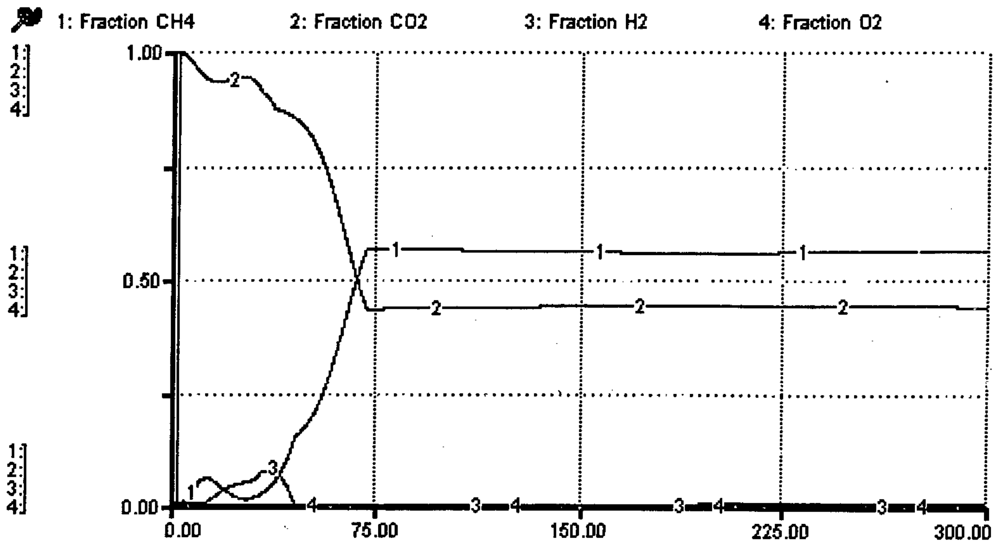


Figure 8. Basic Output of Benter Model (Benter, 1999: 32)

weaknesses that need to be studied further. The most important weakness in the model, which is a carryover from the Colborn model, is the effect of moisture on bacteria and degradation. As stated above, this weakness will be investigated in this thesis.

Factors Influencing Moisture Content

Moisture content of the solid waste in a landfill during active degradation of organic compounds is perhaps the most important in-situ factor affecting the rate and nature of biological transformation and, therefore, the quantity and rate of landfill gas generation (Leckie and others, 1979: 341). Since moisture is a significant factor in degradation, all sources of moisture must be considered important when trying to understand and model the biological processes. Figure 9 illustrates some, but not all, of the sources of water into the landfill.

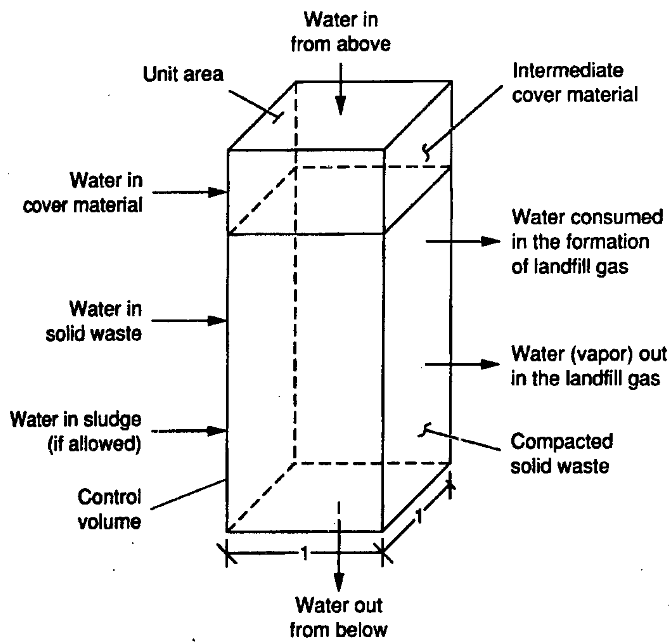


Figure 9. Sources of Water into Landfill (Tchobanoglous and others, 1993: 421)

Initial Moisture Content of Waste. When solid waste is placed in a landfill, it has an initial moisture content. This water content comes from both the inherent moisture in the waste material and from moisture that has been absorbed from rainfall or the atmosphere. This initial moisture content is highly variable and can change dependent on the climate and storage conditions (Tchobanoglous and others, 1993: 422). Although it can vary from 15-40 percent, the initial moisture content of municipal solid waste (MSW) is typically about 20 percent (Tchobanoglous and others, 1993: 72; Palmisano and Barlaz, 1996: 11).

Moisture Content of Cover Material. Water entering the landfill in the cover material is dependent upon the type of material used and environmental conditions. The field capacity of the cover material will determine the maximum amount of water that can be contained in the material. For example, field capacity values range from 6-12 percent for sand to 23-31 percent for clay loams (Tchobanoglous and others, 1993: 422). For cover materials like shredded tires, moisture content depends upon the particle size and is probably less than 5 percent. Environmental conditions include climate, rainfall, and the amount of water purposely added to the daily cover, if any.

Field Capacity of Waste. The field capacity of the waste is the amount of water that can be held by a waste sample, both in the waste and the void spaces, against the pull of gravity (Tchobanoglous and others, 1993: 73). It is a function of the waste composition, age, density, porosity, and landfill depth (Reinhart and Townsend, 1998: 87). As decomposition and compaction of the solid waste occurs in the landfill, the field capacity will progressively decrease from its initial value at the time of placement (Blight, 1995: 11). In dry climates, the field capacity of the waste may never be naturally reached. Conversely, in a wet climate, the waste may be at its field capacity at the time of placement. Table 2 shows that field capacity can be highly variable.

There are several ways to calculate field capacity. One of the most common methods is the following equation (Tchobanoglous and others, 1993: 424):

$$FC = 0.6 - 0.55\,[W / (10{,}000 + W)]$$

where FC = field capacity (the fraction of water in the waste based on the dry weight of the waste)
W = overburden weight at the mid-height of the waste

Users of this equation need to understand that the results are dry weight values. A majority of moisture percentages and calculations, including the ones used in this research, are based on wet weight percent moisture.

Table 2. Values for Field Capacity Reported in Literature (Reinhart and Townsend, 1998: 87)

Field Capacity (% wet weight)	Density (lb/yd^3)
53	359
54	843-1350
43-50	843-1350
53	1160-1600
47	1200
20-30	1038
20-35	1160
36.8	520
28.6	485
31-48	850
48	735
35	800

Biodegradation and Landfill Gas Generation. During the aerobic and anaerobic transformation of solid waste, water can be both produced and consumed. However, aerobic degradation is a net water producer and anaerobic degradation is a net water consumer (Tchobanoglous and others, 1993: 422). The amount of water produced or consumed is dependent upon the rate of the decomposition reactions.

Also, during the biodegradation of the waste, the landfill gas that is generated is usually saturated in water vapor (Tchobanoglous and others, 1993: 423). As the gas escapes into the atmosphere or is collected by the gas collection system, the water vapor is carried out of the landfill. The amount of water lost depends on the gas generation rate.

Environmental Precipitation. Precipitation, especially rainfall, can have a dramatic impact on the moisture content of the solid waste (Leckie and others, 1979: 341). The solid waste is exposed to precipitation throughout its disposal lifetime, from the time it is placed in an outside storage container to when it is placed in the landfill. Even after the solid waste is buried in the landfill, it is exposed to precipitation percolating through the daily cover material and the final landfill cap.

Artificially Added Water. Water can be artificially added to the solid waste in two ways: prewetting of the waste just after it has been placed in the landfill and cycling water through the landfill after the waste has been buried. Prewetting is accomplished by using water trucks or hoses and can be very labor intensive. Prewetting has been practiced for many years as a method for increasing compaction efficiency (Reinhart and Townsend, 1998: 122).

The most common way to cycle water through a landfill is by the recycling of leachate through a recirculation system. The most practical and efficient recirculation methods are the horizontal or vertical systems or a combination of both (Reinhart and Townsend, 1998: 128).

Moisture Content of Added Sludges. Sewage sludges can bring a substantial amount of water into a landfill and raise the moisture content of the solid waste. However, government regulations may limit or not allow placement of sewage sludges in a MSW landfill (Tchobanoglous and others, 1993: 372). Therefore, at this time, sludges are a limited source of solid waste moisture content.

Factors Affecting Water Movement

Water movement, like moisture content, has a significant impact on solid waste degradation and landfill gas generation (Klink and Ham, 1982: 29). Therefore, water movement through a landfill must be considered in conjunction with moisture content when modeling the biological processes. Water movement though a landfill can be affected by multiple factors. Figure 10 shows some, but not all, of the factors affecting water movement.

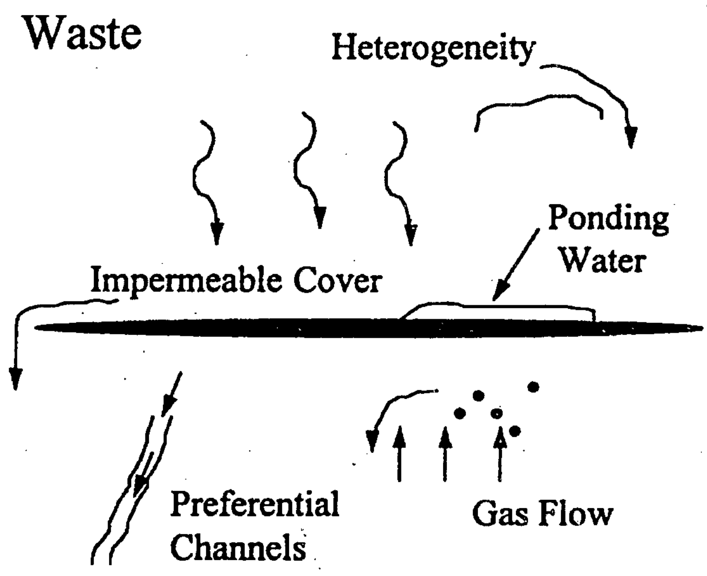


Figure 10. Factors Affecting Water Movement Through a Landfill (Reinhart and Townsend, 1998: 91)

Heterogeneity of Solid Waste. A MSW landfill is an extremely heterogeneous environment that includes both permeable and impermeable wastes. In addition, particle size of waste ranges over many orders of magnitude due to the presence of large materials such as sealed plastic bags, carpet, and plastic sheeting (Reinhart and Townsend, 1998: 90). Because of this heterogeneity, leachate distribution and movement in the landfill will be greatly uneven and variable. One method to improve leachate movement and infiltration throughout the landfill is to shred the waste prior to placement (Murphy and Brennan, 1992: 4). This will reduce the particle size of the waste and, therefore, improve leachate flow and provide a more even distribution of water.

Shedding the waste also reduces the channeling of leachate. Channeling, or fingering, results in the rapid downward movement of leachate through interconnected pores and prevents uniform distribution throughout the landfill (Reinhart and Townsend, 1998: 91).

Cover Material Permeability. The permeability of the intermediate and final cover materials drastically effects water movement into and throughout the landfill. If the cover material has a low permeability, vertical water movement can be severely limited or even stopped. Examples of low permeability materials are clay soils and geomembranes. These materials promote horizontal flow and pooling of water and leachate (Reinhart and Townsend, 1998: 90).

Compaction and Settlement of Waste. Excessive compaction of the waste during placement may adversely impact leachate routing and prevent even moisture distribution (Reinhart and Townsend, 1998: 4). This is due to a reduction in the void space within the waste. Settlement, the settling of the waste as it biodegrades, has a similar impact.

Landfill Gas Flow. Due to the increased gas flow rate, landfill gas production tends to block moisture paths in the landfill during early landfill operation. As gas production declines, these flow paths reopen to leachate flow (Reinhart and Townsend, 1998: 90).

Volume and Frequency of Added Water. The volume of water added to a landfill and the frequency of the addition will directly impact water movement. Once the field capacity of the waste sample has been exceeded, adding more water above the waste will lead to increased water flow through the landfill. However, as the capacity of the leachate collection system is exceeded, water can backup into the landfill and significantly reduce water flow.

Effects of Moisture Content and Movement on Biodegradation and Gas Generation

In the literature, there is no doubt that moisture is needed for biodegradation. Moisture is an essential environmental requirement for the growth of microorganisms, and without the microorganisms, there is no biodegradation and gas generation (Tchobanoglous and others, 1993: 676).

Effects of Moisture Content. In a solid waste landfill, biodegradation may be negatively affected by the limited opportunity for contact between microorganisms, their substrates, and other necessary growth factors. However, as the moisture content is increased, the opportunity for contact is increased, which should enhance microbial activity (Barlaz and others, 1990: 570). Microbial activity rates generally increase to some maximum at an intermediate moisture content (Moorhead and others, 1996: 140).

The moisture content of the solid waste determines the solid-liquid exchange that is useful to enhance the landfill gas generation process (Manna and others, 1999: 4). High moisture content promotes the dissolution and mixing of soluble substrates and nutrients and also provides a mechanism for microbial transport within the landfill (Barlaz, 1997: 543).

With regard to enzyme activity, laboratory results have indicated that extracellular enzyme activities are dependent on solid waste moisture content. It was found that higher moisture content stimulated enzymatic activity in aerobically degrading solid wastes (Jones and others, 1983: 244). Higher protease and amylase activities were reported in saturated waste compared to dry waste. However, no differences could be detected in the cellulase activity (Barlaz and others, 1990: 570). Protease, amylase, and cellulase are the enzymes that degrade proteins, starches, and cellulose, respectively.

The literature, however, is uncertain what moisture content is optimum for solid waste biodegradation. Since landfills are extremely heterogeneous, this uncertainty is expected. The best that the literature can do is provide broad ranges of moisture content for certain conditions. In a majority of the relevant literature, moisture content to promote optimum biodegradation is reported to be from 45-70 percent for anaerobic degradation and about 50-70 percent for aerobic degradation (Murphy and Brennan, 1992: 4). More specifically, for methanogenesis, a moisture content of 50 percent is generally considered desirable (Gurijala and Suflita, 1993: 1178).

Effects of Water Movement. Water movement in a solid waste landfill, which is predominantly obtained through leachate recycle, enhances biodegradation through multiple processes and mechanisms. Some of these processes and mechanisms are the maintenance of improved and uniform moisture levels throughout the landfill, the maintenance and more uniform distribution of optimal pH levels in the range of 6.8 to 7.5, the recycling and distribution of basic nutrients, the dilution of inhibitory compounds, the distribution of enzymes, and the recycling and distribution of methane formers (Klink and Ham, 1982: 39). Also, the continual movement of water through the solid waste accelerates stabilization and increases the rate of waste settlement (Leckie and others, 1979: 353).

Although landfill solid waste contains all the microbes required for biodegradation, the microbes are not well distributed among all the biodegradable components of the waste (Barlaz, 1997: 544). Water movement from leachate recycle enhances the uniform distribution of these microbes. In addition, the establishment of active anaerobic microbial population within the landfill is significantly increased through the recirculation of leachate (Leckie and others, 1979: 353). Water movement through a landfill also stimulates microbial activity by providing better contact between insoluble substrates, soluble nutrients, and the microorganisms (Barlaz and others, 1990: 571). Furthermore, water movement through decomposing solid waste had a residual effect, which gave rise to continued high methane generation rates even after leachate recirculation had stopped (Klink and Ham, 1982: 40).

Surprisingly, the total anaerobic microorganism population in a solid waste landfill remains the same regardless of moisture content and leachate recycle (Barlaz and others, 1992: 266). Therefore, any differences in methane generation rates between leachate recycle and nonrecycle are attributed to the mixing and distribution associated with leachate recycling.

Despite the fact that little research has focused on quantifying the effects of water movement through landfills, there is a general consensus in the literature that water movement does enhance biodegradation. One study concluded that moisture flow increased the rate of methane generation by 25-50 percent relative to waste at the same moisture content with no moisture flow (Klink and Ham, 1982: 39).

Moisture in Gas Simulation Models for Solid Waste Landfills

Previous modeling of the effects of moisture on landfill gas generation is extremely limited. In "Gas Simulation Models for Solid Waste Landfills," El-Fadel et al. summarizes the lack of previous modeling attempts in the following statement:

> Moisture content, pH, and temperature are perhaps the only three variables for which there is quantitative data (not adequate by any means) that may support the development of mathematical functions that are capable of simulating their respective effects on landfill processes. Few models, however, attempted to incorporate these variables in conjunction with gas generation and transport models (El-Fadel and others, 1997, 268-269).

The Colborn and Benter system dynamics models use moisture content as an input for aerobic and anaerobic hydrolysis and all bacteria growth calculations. However, their attempts to model moisture influence are extremely limited and generic. The Colborn model has a moisture structure that consists of a moisture stock value with inflows and outflows. The values and rates of the flows are stoichiometricly determined by how much moisture is produced or consumed in the physical, chemical and biological processes simulated within the model. The moisture stock value, along with the organic waste and simpler substances stock values, is then used to calculate the dry weight percent moisture of the organic waste:

% Moisture (Dry Wt) = Moisture / (Organic Waste + Simpler Substances)

The model then uses a graphical function that calculates a moisture factor based on this percent moisture (Figure 11). This moisture factor is then multiplied into the hydrolysis and bacterial growth rate flow calculations. According to his graphical function, as moisture content increases, hydrolysis rate and all bacterial growth rates will increase up to 1.5 times their assumed ideal values (Colborn, 1997: 64). Colborn uses an initial percent moisture value of 40% (dry weight).

The Benter model makes two changes to the moisture structure used in the Colborn model. The first change was made to the method used to calculate the percent moisture. Instead of using the dry weight calculation for percent moisture, Benter uses

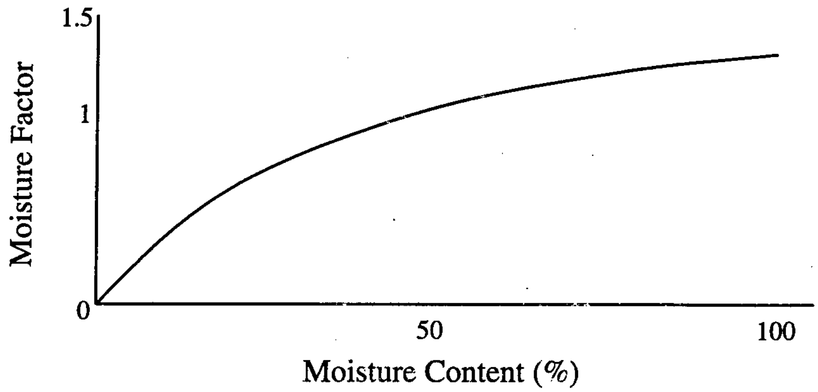


Figure 11. Colborn Graphical Function of Moisture Factor (Colborn, 1997: 64)

the wet weight method to calculate percent moisture. Percent moisture (wet weight) is determined by the following equation:

% Moisture (Wet Wt) = Moisture / (Organic Waste + Simpler Substances + Moisture)

The difference is that the moisture stock value is now added in the denominator. Using the dry weight percent moisture method, the percent moisture can exceed 100 percent. In the wet weight method, the percent moisture cannot exceed 100 percent. The second change to the moisture structure is made to the graphical function used to determine the moisture factor. The moisture factor was changed to a maximum of 1.0, instead of the factor having a maximum of 1.5 (see Figure 12). In the Benter model, as moisture content increases, hydrolysis rate and all bacterial growth rates will increase up to their assumed ideal values (Benter, 1999: 6-7). Except for these two changes, the Benter moisture structure is exactly the same as the Colborn structure. Benter also uses an initial percent moisture of 40 percent. However, his percent moisture is based on the wet weight.

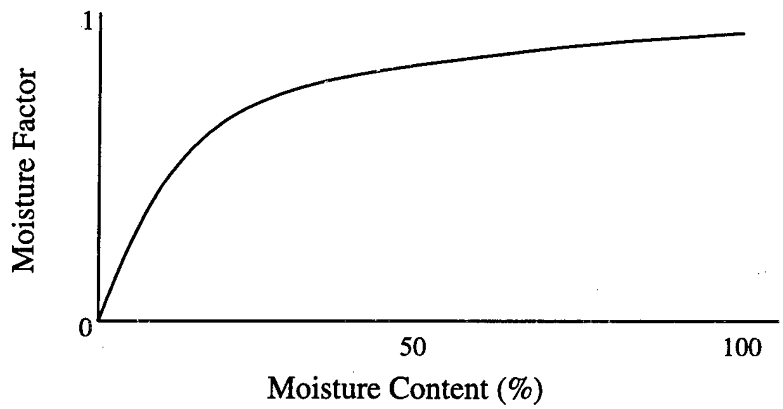


Figure 12. Benter Graphical Function of Moisture Factor (Benter, 1999: 6-7)

III. Methodology

Background

Captain Philip Colborn has used system dynamics to model the fundamental processes of biodegradation in a landfill. System dynamics was used because it captures the feedback loops, multiple interactions, time sensitive behavior, non-linear reactions, and changes in the system over time associated with complex systems like a landfill bioreactor (Colborn, 1997: 43). Captain Brian Benter continued to improve on the bioreactor system dynamics model by addressing the weaknesses contained in the hydrolysis phase of the Colborn model.

This thesis will improve on the Colborn and Benter models by continuing with the system dynamics process and researching and modeling the effects of moisture content in a solid waste landfill. The system dynamics modeling process is usually broken down into four stages: conceptualization, formulation, testing, and implementation. This process is not a linear process. Instead, it is an iterative process during which the model builder can return to and move between any of the four stages to ensure that the model is a correct mechanistic representation of the biodegradation process (Colborn, 1997: 44).

Conceptualization

The main focus of the conceptualization stage of model construction is to become familiar with the general problem area, develop organizing concepts, and develop a mental model (Shelley, 1999). To perform the previous steps and reach an understanding of the problem area involves interacting with experts in the field of study, conducting a literature review, developing a reference mode, and constructing an influence diagram.

Literature Review. Interacting with experts and reviewing literature helps bring the problem area into focus and begins the process of conceptualizing the model and its behavior. Similar to the Benter thesis, this thesis will not be building a model from scratch. Instead, this work will be adding to and improving the existing biodegradation system dynamics model. Therefore, the focus of the literature review for this thesis will be on what impacts moisture content in a landfill and how this moisture content effects biodegradation and gas generation. This specific focus on moisture will lead to a better understanding of how the model can be improved.

Reference Mode. A reference mode is the time development or behavior of a system over a range of interest. In short, it is what is expected from the initial output of the model. The reference mode can be derived from historical data or it can be hypothesized from a general understanding of the system. Any mechanism not believed to be a major impact on the reference mode should not be included in the model (Shelley, 1999). This thesis will continue to use the reference mode used by both Colborn and Benter. This reference mode is based on the phases of landfill gas generation during waste degradation. These phases are illustrated in Figure 1. The reference mode is discussed and illustrated in Chapter 4 (Figure 13).

Influence Diagram. An influence diagram illustrates the cause and effect relationships and structure suggested by the reference mode (Shelley, 1999). It is usually constructed using relevant literature and information from experts in the field. For biodegradation, an influence diagram would incorporate the cause-and-effect relationships between the important mechanisms that best represent the biodegradation process. Two examples are the influence diagrams constructed by Colborn in Figure 3 and Benter in Figure 6. A positive sign (+) denotes a positive interaction and a negative sign (-) denotes a negative interaction between the entities. The influence diagram for this research will incorporate the cause-and-effect relationships between the waste, moisture, bacteria growth, and biodegradation. Influence diagram construction, like the system dynamics modeling process, is iterative and the diagram should be modified, when needed, to achieve the most accurate causal diagram.

Formulation

After the reference mode and influence diagram have been established, the systems modeling process moves into the formulation stage. This stage begins with the transformation of the influence diagram into a flow diagram. A flow diagram translates the notional influence diagram into a real operating system representation that complies with the logic represented in the influence diagram. The flow diagram explicitly identifies what entity is a level (or stock) and what is a rate or flow (Shelley, 1999). Figure 4 in Chapter 2 is the flow diagram constructed by Colborn from the influence diagram in Figure 3. Stocks, represented by rectangles, are accumulations that are defined by their inflows and outflows. Material flows in and flows out according to the corresponding flow rates. Flows, symbolized by arrow-circle combinations, represent the flow of material into and out of a stock. Flow rates are in units of stock per time and can be constant or continuously calculated using parameter inputs (Shelley, 1999). For example, in Figure 4, some flow rate inputs include stoichiometric ratios, bacterial growth rates, and environmental parameters.

Once a workable flow diagram has been constructed, the system dynamics model is built by coding the flow diagrams into the appropriate systems software. Basically, the software transforms stocks and flows from the flow diagrams into differential equations and solves them using traditional numerical integration techniques (Colborn, 1997: 49). This research will continue to use the same software package as Colborn and Benter. Although the software has been upgraded, the basic operation of the model remains the same. This software is STELLA Research 5.1.1 by High Performance Systems, Inc.

The formulation for this model will consist of two stages. The first stage will consist of improving the moisture structure within the current model boundaries. The second stage will expand the boundaries of the model and formulate outside flows into and out of the moisture stock.

Testing

For a system dynamics model to be useful there must be confidence in its operation and behavior. Building this confidence requires that the model be run through tests to validate its scope, structure, behavior, parameters, and reflection of the reference mode. Since the existing model has already been shown to reflect the reference mode, tests will be run to determine the impact of the added moisture structure and the plausibility of the moisture parameters. Any deficiencies will be corrected as the model is tested. As more and more tests are passed, confidence is slowly accumulated in the system dynamics model (Forrester and Senge, 1980: 209).

Structure Verification Test. This test compares the structure of the model directly with the structure of the real system that the model represents. Conducting this test involves comparing the model to relevant literature and review by experts and advisors.

To pass this test, the model structure must not contradict knowledge about the structure of the real system (Forrester and Senge, 1980: 212). However, to prevent unneeded complexity, the structure does not have to include every aspect of the real system to pass the test.

Parameter Verification Test. Similar to the structure verification test, this test compares the parameters used in the model to real system values. The test determines if the parameters correspond conceptually and numerically to real life (Forrester and Senge, 1980: 213).

Extreme Conditions Test. This test is used to determine how a model reacts to extreme conditions and it is a valuable test for discovering flaws in a model. Structure in a system dynamics model should permit extreme combinations of variables in the system being operated. The test involves changing variables to credible minimums and maximums and determining if the model reasonably reacts to these changes. The whole model should be questioned if the extreme-conditions test is not met (Forrester and Senge, 1980: 213-214). If the test is passed, confidence is built in the model's ability to react plausibly under a wide range of conditions.

Sensitivity Test. The extreme conditions test examines how the model behaves at the extreme values for parameters. However, the behavior caused by two extreme values does not give a full picture of system behavior between the two extremes. It is beneficial to model understanding when system behavior for a range of values is known (e.g. linear or exponential relationship). The sensitivity test will reveal how the model behaves when changes are made to the parameter values between those extremes.

Boundary Adequacy Test. This test determines whether or not the model includes all relevant structure needed to address the model's scope and purpose. It also determines if any structure of the model is beyond the initial boundary considered for the model. The test involves conceptualizing additional structure that might influence behavior. After conceptualizing additional structure, the model is tested with and without the new structure to determine its effect. If the additional structure does not significantly change the behavior of the model, then the model does not need to incorporate that structure.

Implementation

The implementation stage for this research will consist of several model runs to simulate how the model could be implemented in the field to aid the landfill management process. Parameters and conditions in the model will be changed and recommendations will be made about how a landfill manager could change inputs (e.g. initial moisture content or water infiltration flow rate) to optimize biodegradation and methane generation based on these conditions and parameters. This implementation stage will just be a thumbnail sketch on how the model can be utilized in real landfill management, which is the ultimate goal for the model.

IV. Results and Discussion

Conceptualization

Reference Mode: The reference mode for this research will be the same as the one used in the Colborn and Benter models. This reference mode is shown in Figure 13. It is not an exact replica of the generalized phases of landfill gas generation as shown in Figure 1. The atmospheric nitrogen and oxygen gases in Figure 1 have been replaced with 100 percent oxygen. This is done because atmospheric nitrogen, which makes up 80% of air, suppresses the relative contribution of microbially generated hydrogen gas within the landfill. Figure 13 corrects the relative concentration of hydrogen gas in the absence of atmospheric nitrogen (Colborn, 1997: 54).

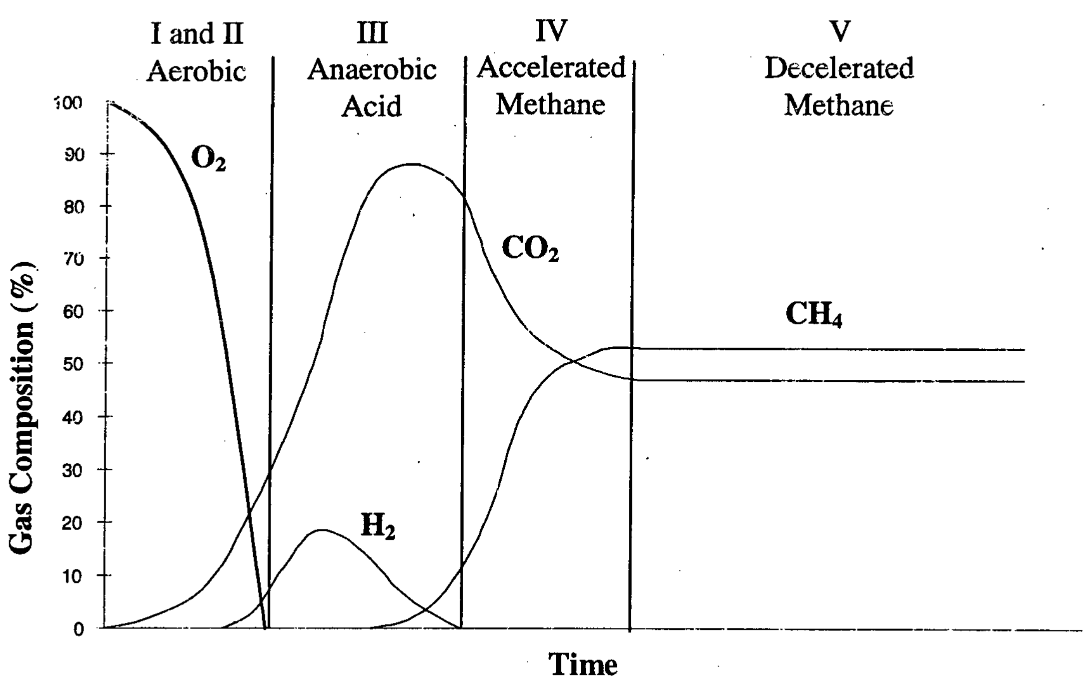


Figure 13. Theoretical Reference Mode (Colborn, 1997: 55)

Influence Diagram: Utilizing the literature review and the Colborn and Benter influence diagrams, an influence diagram illustrating the cause-and-effect relationships between moisture content and biodegradation was constructed (Figure 14).

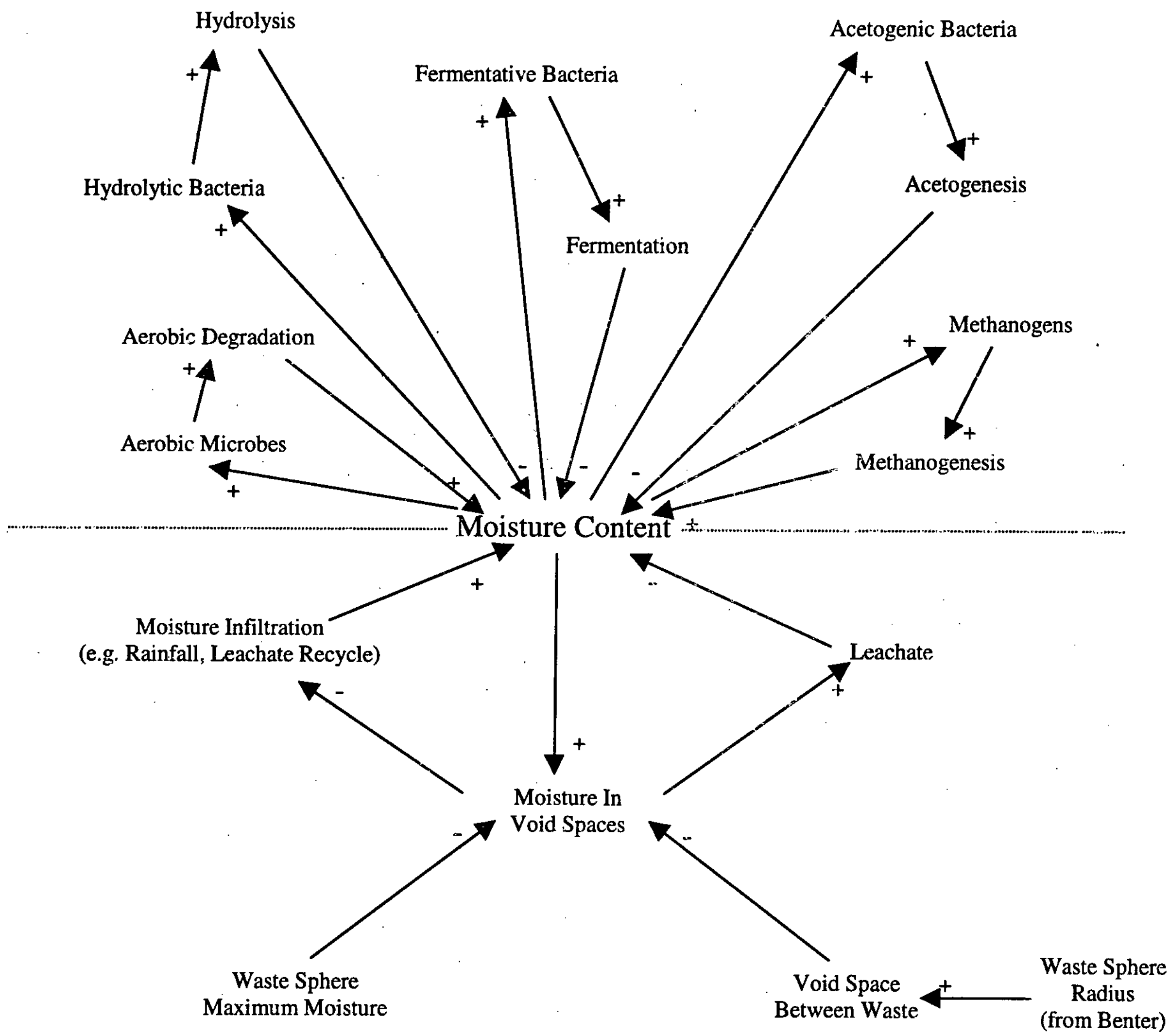


Figure 14. Moisture Influence Diagram

In Figure 14, the section above the dotted line was already incorporated into the Colborn and Benter influence diagrams. This influence diagram simply pulls the information from their diagrams and makes it easier to read. The section below the dotted line consists of new inputs for the moisture content. Waste sphere maximum moisture and percent moisture in the void spaces are key inputs because the Colborn and Benter models only calculated a generic percent moisture value. This percent moisture value did not illustrate or take into account the amount of water in the waste and in the void spaces. The two new variables will give a fuller picture of the moisture conditions.

To summarize from Chapter 2, Benter based his hydrolysis degradation on the assumption that the solid waste is present in the landfill in the form of waste spheres. These waste spheres are degraded only on the surface of the sphere. This waste sphere assumption is continued in this research and is used to formulate a variable called waste sphere maximum moisture. Waste sphere maximum moisture is a variable that is similar to waste field capacity. Waste field capacity is the amount of water that can be held by a waste sample against the pull of gravity. Waste sphere maximum moisture will be used in this model as a measure of the maximum percent moisture (wet weight) that can be held by the individual waste spheres against the pull of gravity. The difference between the two variables is where the water is held. In waste field capacity, the water is held in the whole waste sample (waste and voids spaces). In the waste sphere maximum moisture variable, the water is held in only in the waste spheres. Therefore, waste sphere maximum moisture will be less than the waste sample field capacity. Field capacity is not contained in the name of the new variable to avoid any misunderstanding about the how the water is accounted for in the two different variables and definitions.

Percent moisture in the voids is a variable that is calculated using percent moisture, waste sphere maximum moisture, and void space between the waste (i.e. air). Once the percent moisture exceeds the waste sphere maximum moisture, water starts to fill the void spaces between the waste. The method used to determine the amount of void space between spheres of waste is illustrated in Figure 15. A 3-dimensional "box" of void space is assumed to surround the waste sphere. All the spheres in the landfill have this assumed box around them. The amount of void space is then calculated by subtracting the volume of the waste sphere from the volume of the box. The total amount of void space is the amount of void space in one box multiplied by the total number of spheres. The volume of each sphere is calculated using Benter's assumption that each waste sphere has a radius of 7 centimeters. As the volume of the waste is depleted (radius decreases), the size of the box (and the amount of void space) will also decrease. The spheres are not assumed to be tightly packed (i.e. a tighter staggered arrangement) because waste in a landfill is heterogeneous and is not neatly packed. Instead, the landfill will have large void spaces caused by irregularly shaped waste and insufficient compaction.

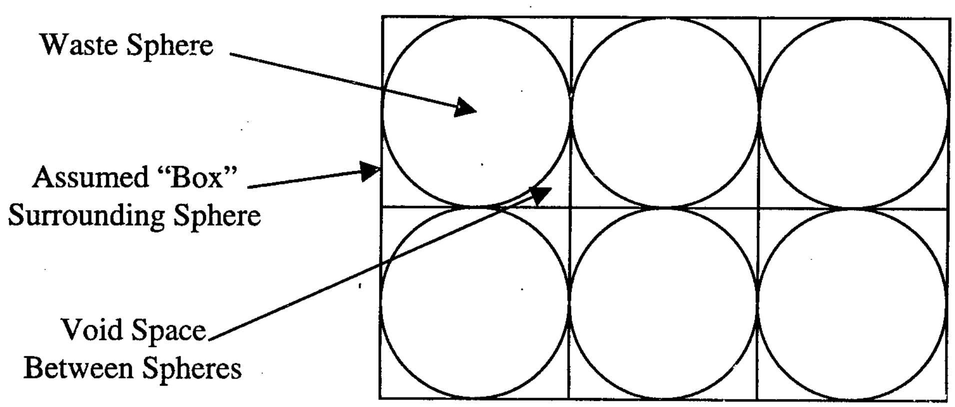


Figure 15. Assumed Arrangement of Waste Spheres Used to Calculate Void Space

After the above variables have been added to the model and their impacts investigated and tested, the boundary used by the previous two models will then be expanded and relevant influences added to simulate outflow and inflow of moisture. These two flows are shown in the influence diagram as leachate and water infiltration. These flows are more representative of the flow of moisture in a landfill and they more closely replicate the "wet-cell" concept of adding moisture to accelerate the landfill processes.

When the two added flows are placed in the model, they will introduce two negative feedback loops into the system. The first negative feedback loop is the relationship between moisture content, percent moisture in the void spaces, and leachate. As already stated above, an increase in moisture content will cause an increase in percent moisture in the void spaces. This causes an increase in leachate, which will cause a decrease in moisture content. Leachate rate will be dependent upon the amount of moisture already in the system. As the amount of moisture in the system increases towards saturation, leachate flow rate will increase. The second negative feedback loop is the relationship between moisture content, percent moisture in the void spaces, and moisture infiltration. Assuming the waste sphere maximum moisture has been exceeded, an increase in moisture content will cause an increase in percent moisture in the void spaces. This will cause a decrease in moisture infiltration, which, in turn, causes a decrease in the flow rate into the moisture stock. Moisture infiltration, specifically leachate recycle rate, will be dependent upon the amount of moisture already in the system. As the amount of moisture in the system increases towards saturation, the rate of moisture infiltration will decrease and ultimately go to zero. This moisture infiltration rate decrease is due to both a natural resistance by the waste to accept the flow of more moisture as it approaches saturation and a conscious effort by the landfill manager to reduce flow as the waste nears saturation. These two loops work together to help control the amount of moisture resident in the system.

Formulation of Initial Moisture Structure Changes

The influence diagram in Figure 14 was used to construct flow diagrams of the new moisture structure. Figure 16 is the flow diagram of the revised relationship between moisture and bacterial growth.

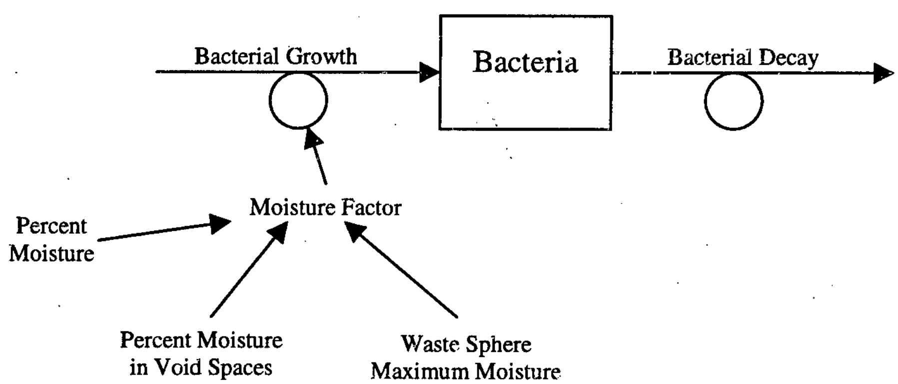


Figure 16. Generic Flow Diagram for Moisture Effects on Bacteria

Like the Colborn and Benter models, this model will contain a moisture factor that affects the rate of hydrolysis and bacterial growth. The moisture factor used in the previous models was graphically calculated using just the percent moisture variable. The moisture factor used in this research will be dependent upon percent moisture, waste sphere maximum moisture, and percent moisture in the void spaces. All three factors, which will be used to calculate a moisture variable, will work together to provide a moisture factor that accounts for moisture conditions below, at, and exceeding waste sphere maximum moisture. Actually, two different moisture factors will be used. One factor is for aerobic processes and the second is for anaerobic processes. The graphical functions used for the aerobic and anaerobic moisture factors are illustrated in Figures 17 and 18, respectively.

The aerobic moisture factor reaches its maximum value of 1 when 50 percent of the voids are filled with water. Then the factor decreases to 0.5 when the waste and voids are fully saturated. This drop-off is due to the increased amount of water serving as a barrier to the oxygen. In other words, the oxygen has a harder time going from the air, into the water and making it to the surface of the waste.

The anaerobic moisture factor reaches its maximum at 100 percent saturation. As discussed in the literature review, the increasing amount of moisture increases the efficiency of all anaerobic processes. In closed systems, there would normally be a drop-off in efficiency near 100 percent saturation. This is due to the detrimental buildup of acids and a lowered pH in pockets of waste. This model assumes that these detrimental effects will not happen, especially when there is a constant flow of water through the waste caused by water infiltration and leachate collection.

The moisture variable used in the moisture factor graphical function is calculated using percent moisture, waste sphere maximum moisture, and percent moisture in the voids. When the percent moisture is less than the waste sphere maximum moisture, all the moisture in the system is in the waste and no moisture is in the voids. This value of the moisture variable under these conditions is:

Moisture Variable = [(1-(percent moisture/waste sphere maximum moisture))*(-100)]
when Percent Moisture < Waste Sphere Maximum Moisture

The range for the moisture variable under these conditions can range from –100 to zero. As percent moisture increases and approaches waste sphere maximum moisture, the moisture variable also increases and approaches zero. Once the percent moisture exceeds waste sphere maximum moisture, the voids begin to fill with water and the value of the moisture variable becomes:

Moisture Variable = Percent Moisture in the Voids
when Percent Moisture > Waste Sphere Maximum Moisture

The range for the moisture variable under these conditions can range from zero to 100.

To summarize, the graph of the moisture variable less than zero accounts for moisture conditions below waste sphere maximum moisture and the graph greater than zero accounts for moisture conditions starting at waste sphere maximum moisture and going up to complete saturation.

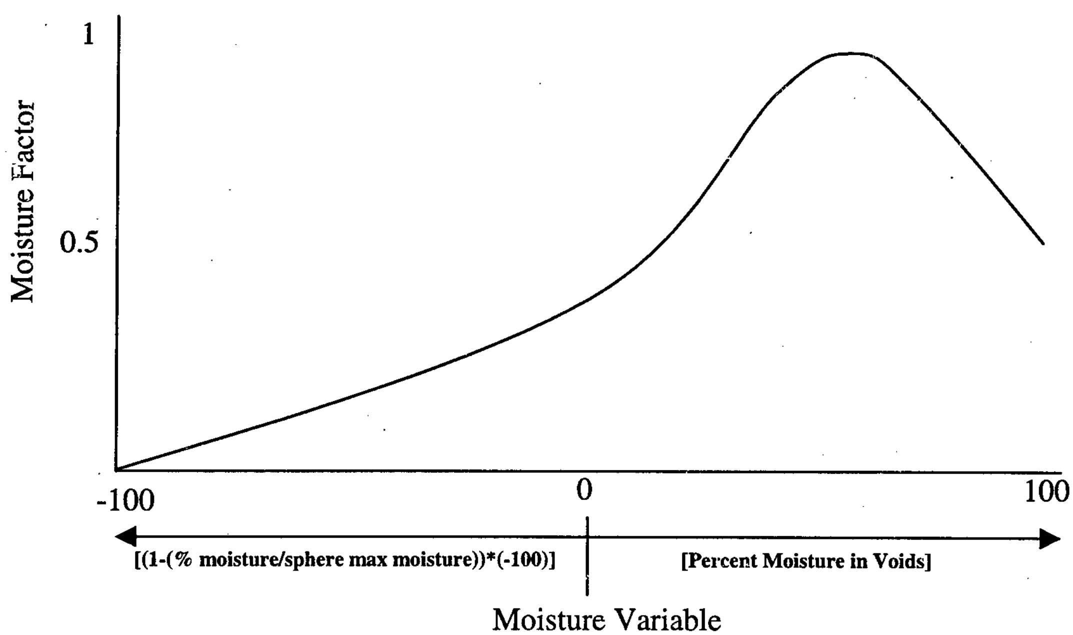


Figure 17. Graphical Function of Aerobic Moisture Factor

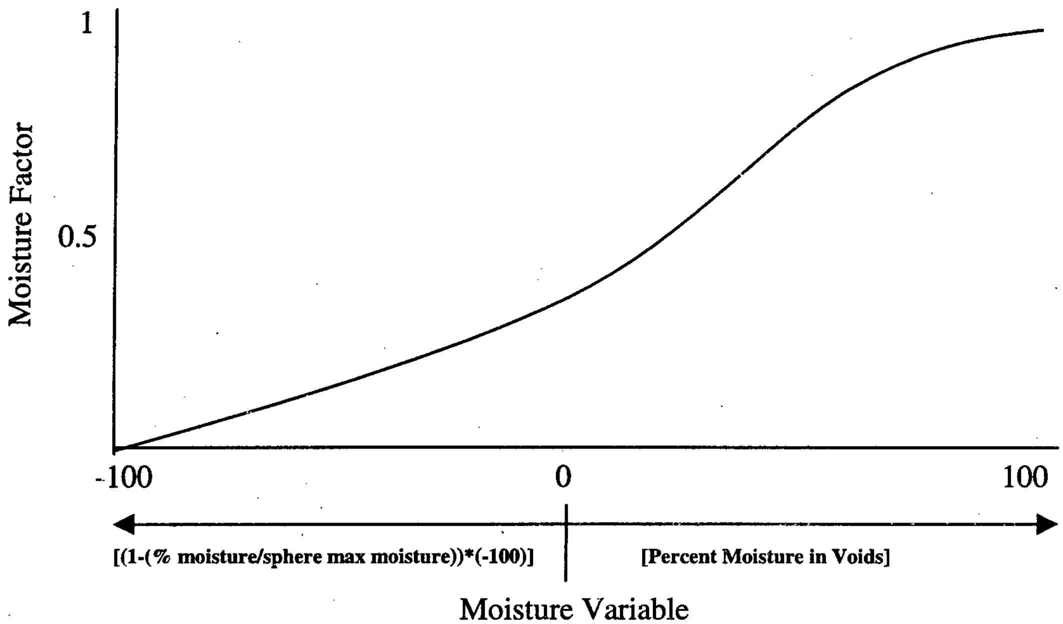


Figure 18. Graphical Function of Anaerobic Moisture Factor

The shapes of the curves in Figures 17 and 18 are consistent with the overall data presented in the literature review. Since there were multiple but diverse sources of data representing the impact of moisture content on solid waste, the above curves are based on a compilation of this data in combination with intuitive analysis. In addition, it is assumed that one aerobic moisture factor graph is sufficient to accurately represent the impact of moisture content on all aerobic processes. The same is assumed for all anaerobic processes.

Testing Initial Moisture Structure Changes

Once the initial changes and additions to the system dynamics model were completed, a series of simulations were performed to compare the new output to the reference mode and the Benter model and to test and validate the model. Figure 19 illustrates the basic output of the model using the initial parameter values similar to the

Benter model. Initial percent moisture was set at 40 percent. The waste sphere maximum moisture variable, not present in the Benter model, was set at an initial value of 35 percent. The basic output is consistent with the Benter model and it reasonably simulates the reference mode. Oxygen is quickly depleted and hydrogen is produced. Carbon dioxide accumulates very quickly and then declines as methane is generated. Carbon dioxide and methane approach a steady state condition at about 90 days into the simulation.

There is one difference between the basic output and the reference mode that was also present in the Benter model basic output. In the reference mode, the hydrogen fraction increases and peaks before the methane fraction begins an observable increase. However, in this and the Benter model basic outputs, the methane fraction increases before the hydrogen fraction. There is a decrease in methane as hydrogen is produced. However, methane fraction increases again as the hydrogen fraction drops to near zero. This observation will be discussed in Chapter 5.

There is one difference between this and the Benter basic output. This difference is when carbon dioxide and methane reach equilibrium. In the Benter output, equilibrium is reached at about Day 65. In the new output, it is reached at about Day 90. This later equilibrium time is an improvement over the previous model because the moisture condition used (40 percent moisture content) is below optimal and gas generation would realistically be slower.

Although 40 percent initial moisture content is used for the basic output in Figure 19, this value was changed to 25 percent to better reflect real system conditions. Figure

21 illustrates the basic output of the model using the new initial condition of 25 percent moisture content. Waste sphere maximum moisture remains at 35 percent.

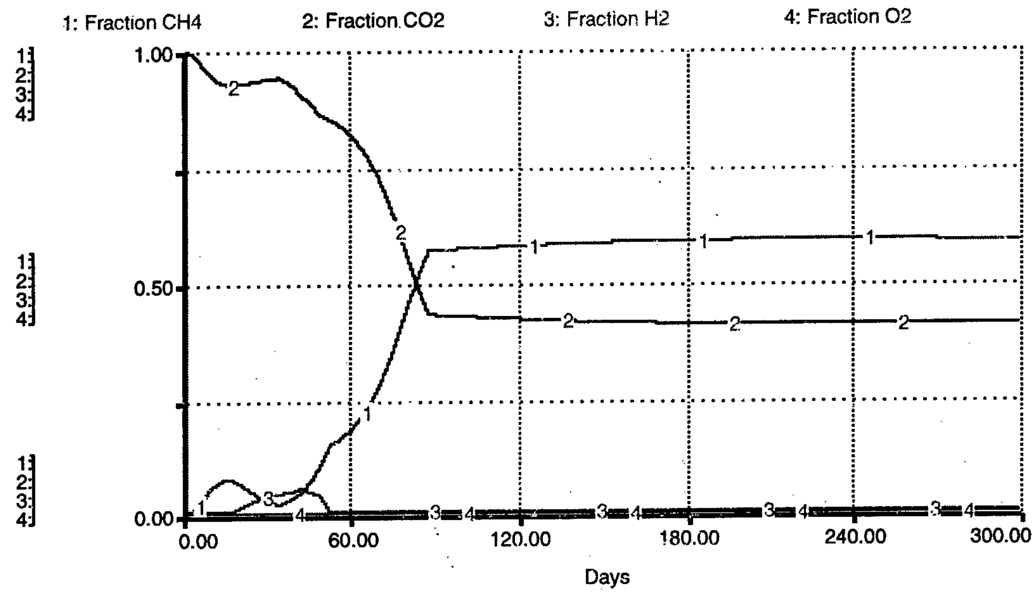


Figure 19. Basic Output of Model Using Benter Initial Conditions

(40 Percent Initial Moisture Content)

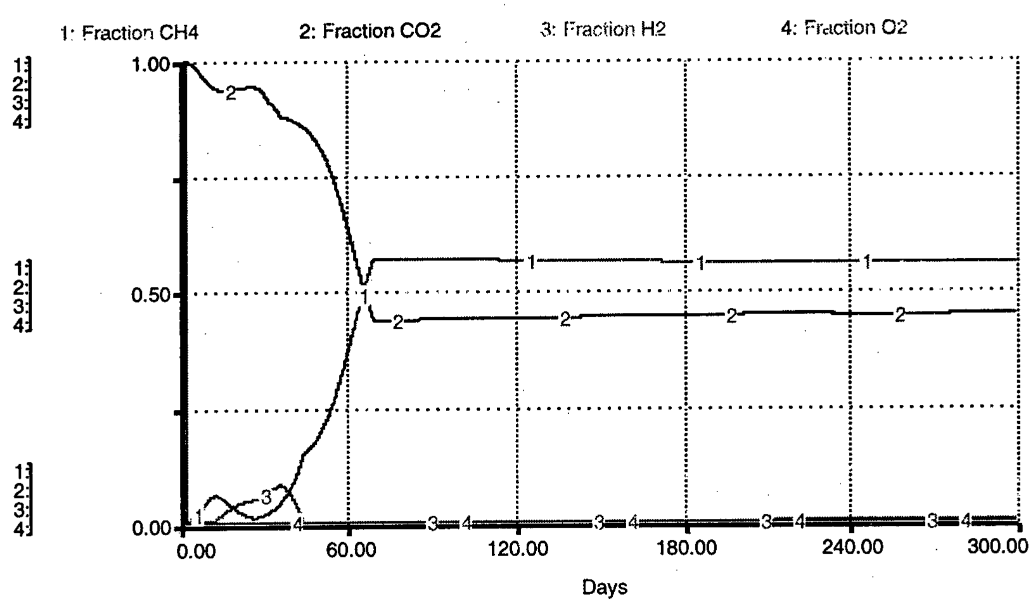


Figure 20. Basic Output of Benter Model (Benter, 1999: 32)

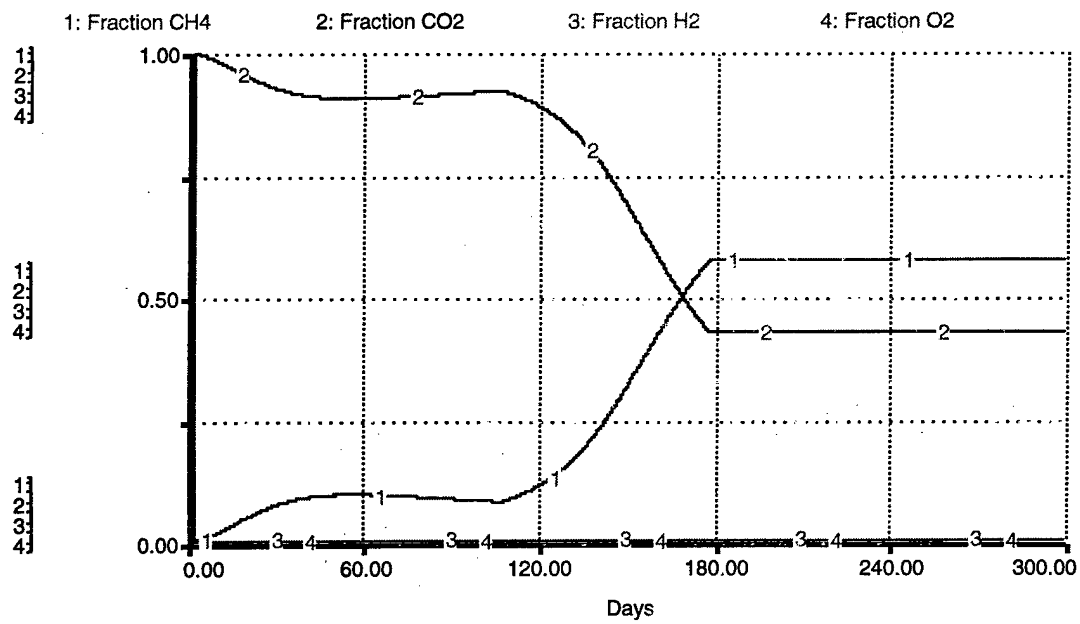


Figure 21. Basic Output of Model Using New Initial Conditions

Figure 21 illustrates the impact of changing initial moisture content to 25 percent. Gas generation processes are slower and equilibrium is not reached until about Day 180. The main difference between Figure 21 and the reference mode is the lack of an observable hydrogen fraction. This is because hydrogen generation is slowed down and hydrogen is not allowed to buildup in the system. It is consumed as a substrate as soon as it is generated. The carbon dioxide and methane relationship remains basically the same, although at a slower rate. Figure 21 is another improvement over the Benter model because it uses an initial content that is more realistic. The 25 percent moisture content and 35 percent waste sphere maximum moisture conditions will be used as the basic moisture conditions for the model and all testing.

Figure 22 is included to illustrate the moisture variable values using the new initial conditions. The maximum percent moisture allowable in the system using these conditions is approximately 55 percent. The percent in the total system starts at about 25 percent and rises slightly due to methanogenesis adding moisture to the system. Also, percent moisture in the voids remains at zero because the percent moisture in the system stays below the waste sphere maximum moisture.

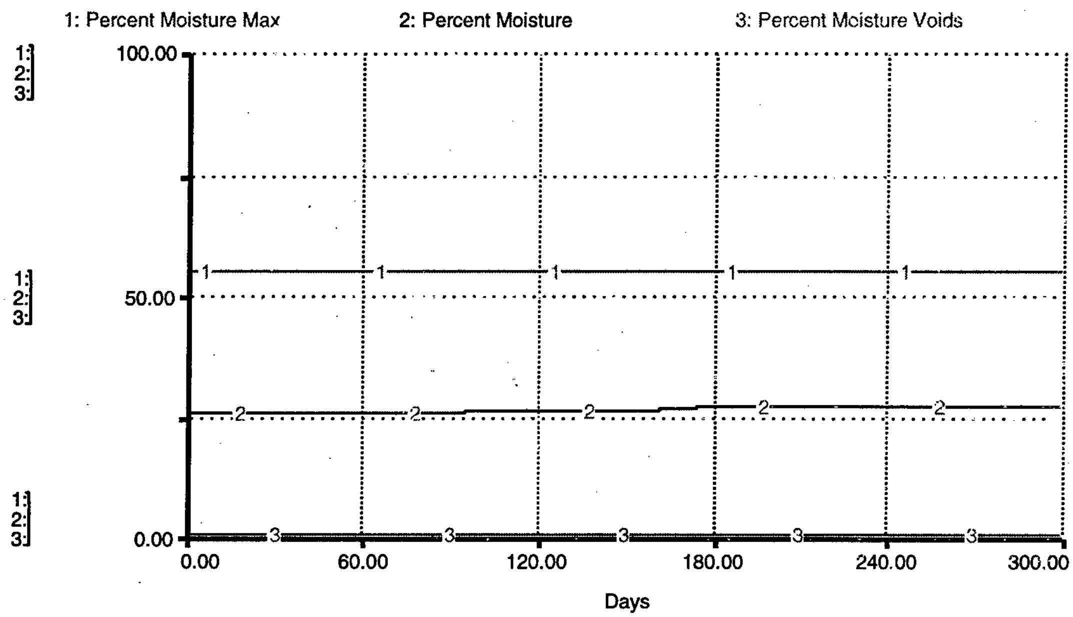


Figure 22. Moisture Variable Values Using New Initial Conditions

Confidence still needs to be built in the model and the simulation of the reference mode is just the beginning of that confidence building. Multiple tests must be performed on the model to validate its structure, parameters, behavior, and scope.

Structure Verification Test. The structure verification test involves comparing the model to the real system that it represents. To pass the test, the model must not contradict the knowledge, both from the literature and experts, about the structure of the real system. The initial structure that was added to the model was based on part of the influence diagram in Figure 14. More importantly, the influence diagram was based on a detailed literature review and discussion with advisors. Therefore, since the influence diagram is supported by real system conditions, so is the model structure. In addition, since the new model structure basic output essentially reproduces the reference mode, the structure is assumed valid and realistic.

Parameter Verification Test. This test determines if the parameters used in the model are realistic and reasonable when compared to the real system. All the parameter values used for the moisture structure were selected based on values in the literature from a real system or from experimental data. A value of 25 percent is used for the initial percent moisture for the model. The percent moisture range for the average solid waste placed in a landfill is 15-40 percent with a typical value of 20 percent. A value of 25 percent was used because organic waste, which is used as the initial waste product in this model, is usually "wetter" than the average municipal solid waste. The literature verifies this value (Tchobanoglous and others, 1993: 72). The waste sphere maximum moisture value used for the initial output was 35 percent. A value specifically representing waste sphere maximum moisture could not be found in the literature. However, a range for the value is calculated using initial moisture content and normal waste field capacity. The average waste moisture content when placed in the landfill is 25 percent. The average field capacity for a waste sample, which is calculated from the data presented in Table 2 in the literature review, is 45 percent. Average waste sphere maximum moisture must be less than normal waste field capacity. Therefore, waste sphere maximum moisture must lie between these two values. After further literature review and discussion with advisors, a value of 35 percent was chosen for waste sphere maximum moisture.

Extreme Conditions Test. This test is used to ensure that the model structure represents realistic influences even in the case of extreme values. This test will focus on moisture structure and the added or changed moisture variables. These variables are initial percent moisture and waste sphere maximum moisture. These two variables have a great impact on biodegradation and their values have the potential to exist at extremes depending on solid waste characteristics, climate, and landfill construction. Testing is successful when extreme conditions are simulated and the output is plausible for these extreme conditions. Different criteria will be used to test the variables. For example, the criteria for the percent moisture variable will be the gas fraction, methanogenic bacteria behavior and total methane generated.

Percent Moisture. Initial percent moisture can realistically range from zero to 100 percent. However, depending on multiple factors, the maximum percent moisture for a given set of conditions can be far less that 100 percent. Therefore, care must be taken in choosing an initial moisture content stock. For example, the basic output using the new initial conditions modeled above results in a maximum possible percent moisture of about 55 percent. At this percentage, no more moisture can physically flow into the system without an equal amount flowing out. Therefore, the initial percent moisture values will be changed to model the extremes of 0 and 55 percent. As stated above, gas fraction, behavior of methanogenic bacteria and total methane generated will be used as a metric to determine the results of these changes.

Figures 23 and 24 show the outcome of changing the initial percent moisture on the gas fraction. The results are as expected. In Figure 23, when moisture content is zero, the gas fraction remains at 100 percent oxygen because there is zero bacterial growth to begin biodegradation. In Figure 24, when moisture content is at saturation, gas generation is accelerated and optimized

Figures 25 and 26 illustrate methanogenic bacteria growth and methane generation under the extreme conditions. Trace 1 for both of the graphs shows the results when initial percent moisture is zero. Trace 2 shows the results when the initial percent moisture is 55 percent and the system is completely saturated. These results are also as expected. When moisture content is zero, bacteria growth and methane generation is zero. When moisture content is at total saturation and conditions start at optimal levels, these processes are accelerated.

<u>Waste Sphere Maximum Moisture</u>. The waste sphere maximum moisture extreme values tested were zero and 90 percent. An extreme value of 100 percent was not used because it is not feasible when waste sphere maximum moisture is based on wet weight. A 100 percent waste sphere maximum moisture would mean that the "waste" is all water and no waste. Zero percent waste sphere maximum moisture means that no moisture is present in the waste and all the moisture exist in the void spaces. A waste sphere maximum moisture of 90 percent means that a large amount of moisture can reside in the waste and very little moisture will make it into the void spaces. It is expected, due to the above conditions, that a zero waste sphere maximum moisture will result in quicker growth and a higher maximum moisture will result in slowed growth. Gas fraction, behavior of fermentative bacteria, and total methane generated will be used as metrics to determine the results of these changes.

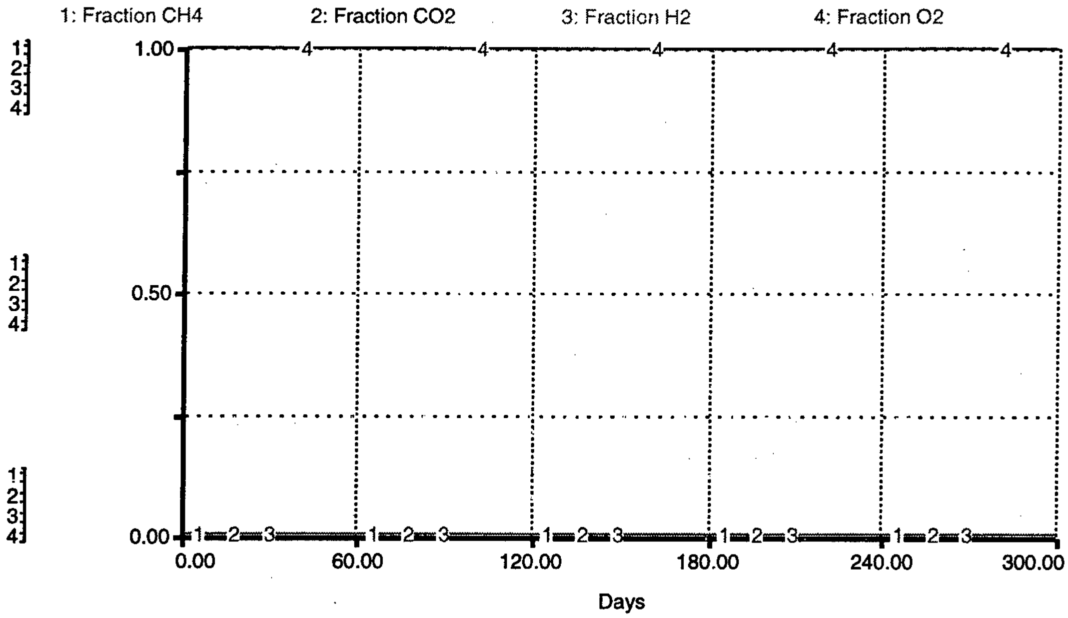


Figure 23. Gas Fraction Under Extreme Percent Moisture Conditions (Zero Percent Moisture)

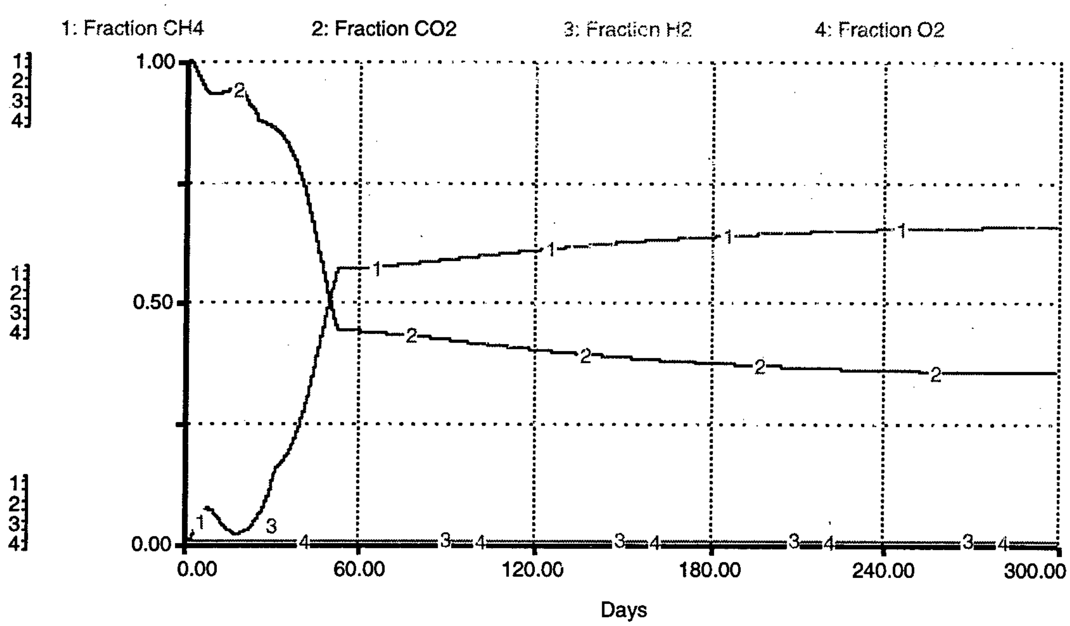


Figure 24. Gas Fraction Under Extreme Percent Moisture Conditions (Saturated)

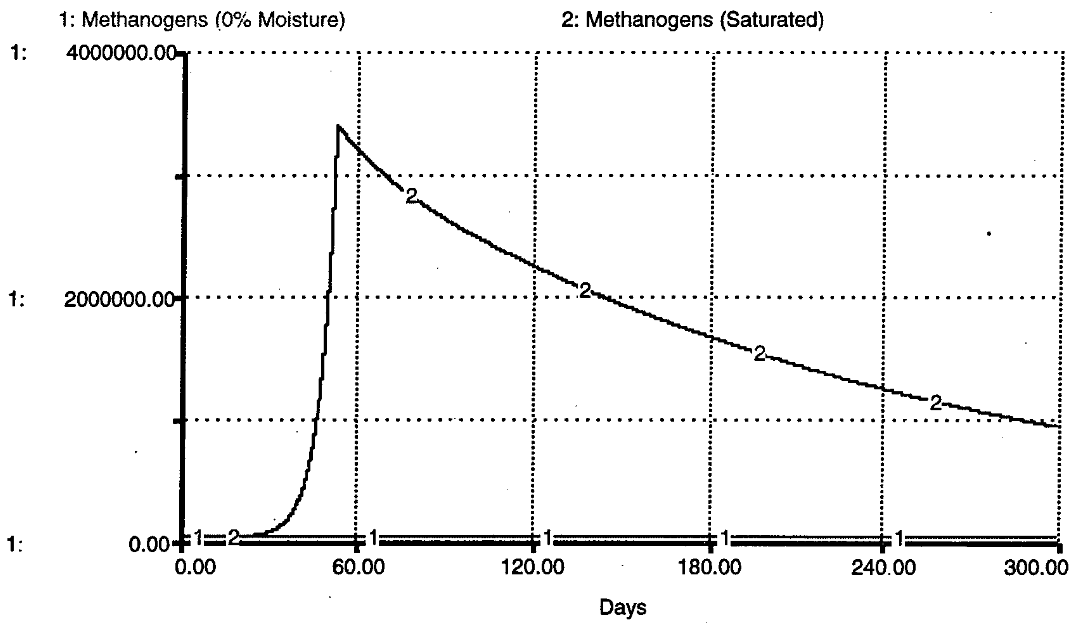


Figure 25. Methanogen Growth Under Extreme Percent Moisture Conditions

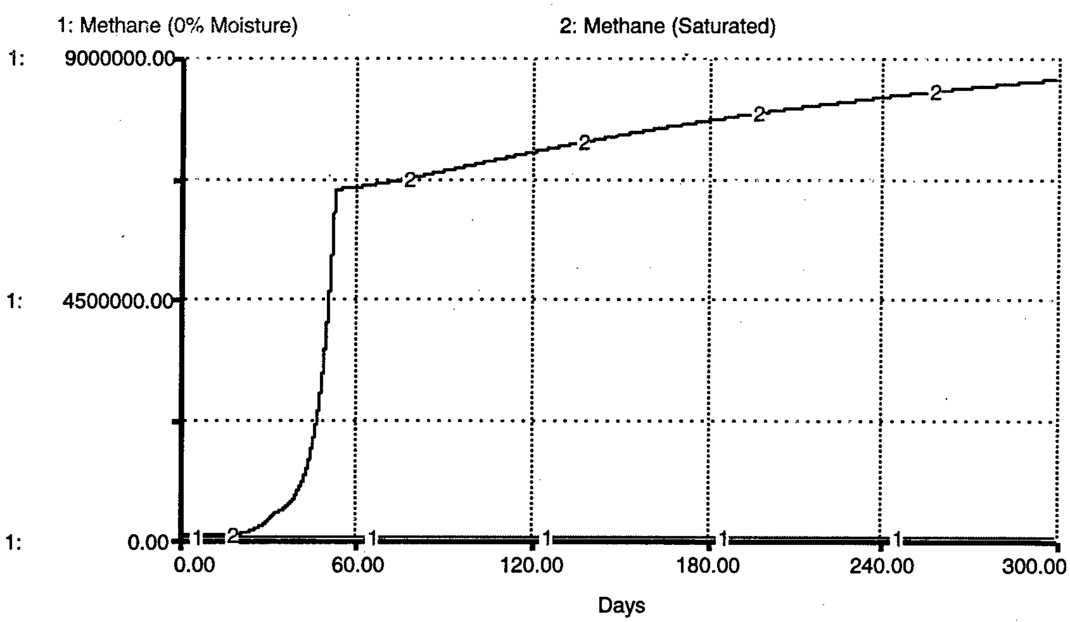


Figure 26. Methane Generated Under Extreme Percent Moisture Conditions

Figures 27 and 28 show the results using the gas fraction graphs. In Figure 27, when the waste sphere maximum moisture is zero and all moisture exists in the voids spaces, gas generation is accelerated compared to initial conditions. In Figure 28, when the waste sphere maximum moisture is 90 percent and all moisture exists in the waste, gas generation is extremely delayed. These figures follow the expected results.

Figures 29 and 30 illustrate fermentative bacteria growth and methane generation under the extreme conditions. Trace 1 for both of the graphs shows the results when waste sphere maximum moisture is zero. Trace 2 shows the results when waste sphere maximum moisture is 90 percent. These results are also as expected. When waste sphere maximum moisture is zero, bacteria growth and methane generation are accelerated. When waste sphere maximum moisture is 90 percent, these processes are slowed and greatly degraded.

Sensitivity Test. The Extreme Conditions Test examined how the model behaved at the extreme values for moisture parameters. However, the behavior caused by two extreme values does not give a full picture of system behavior between the two extremes. It would be beneficial to model understanding if system behavior for a range of values was known (e.g. linear or exponential relationship). The Sensitivity Test will reveal how the model behaves when changes are made to the parameter values between those extremes. This test concentrated on the same variables as the Extreme Conditions Test. These variables are percent moisture and waste sphere maximum moisture. Also, like the Extreme Conditions Test, different criteria were used to test the sensitivity of the variables.

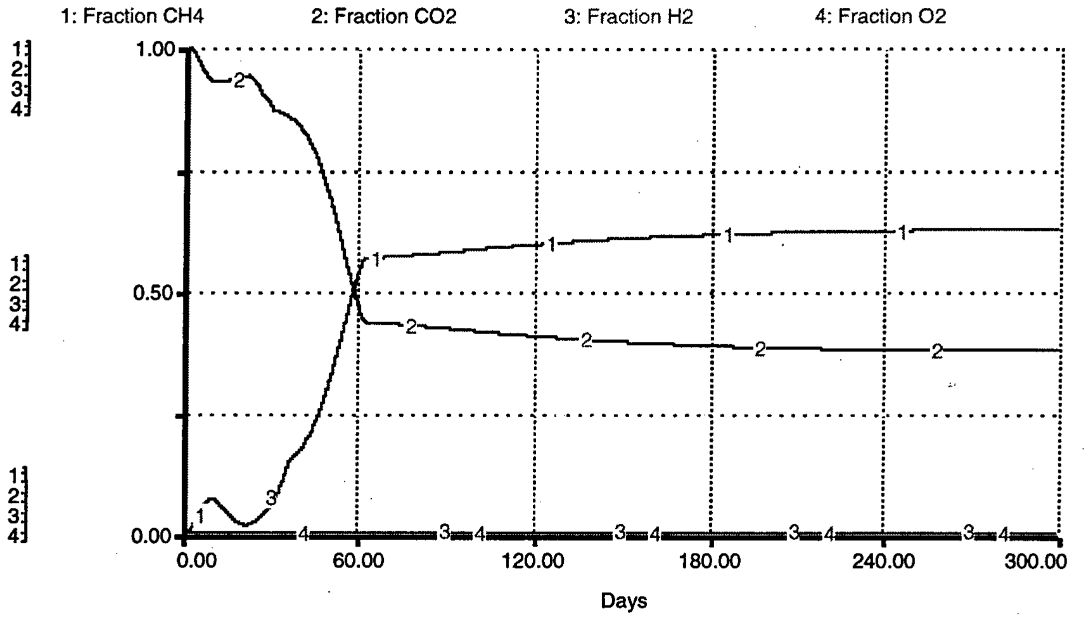


Figure 27. Gas Fraction Under Extreme Waste Sphere Maximum Moisture Conditions (Zero Percent Maximum Moisture)

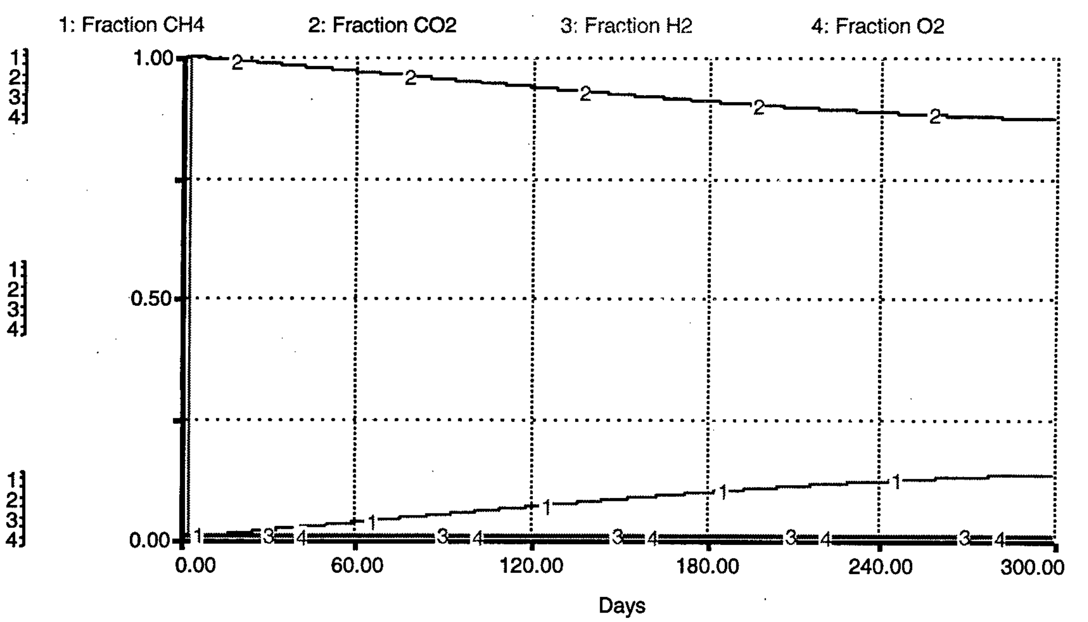


Figure 28. Gas Fraction Under Extreme Waste Sphere Maximum Moisture Conditions (90 Percent Maximum Moisture)

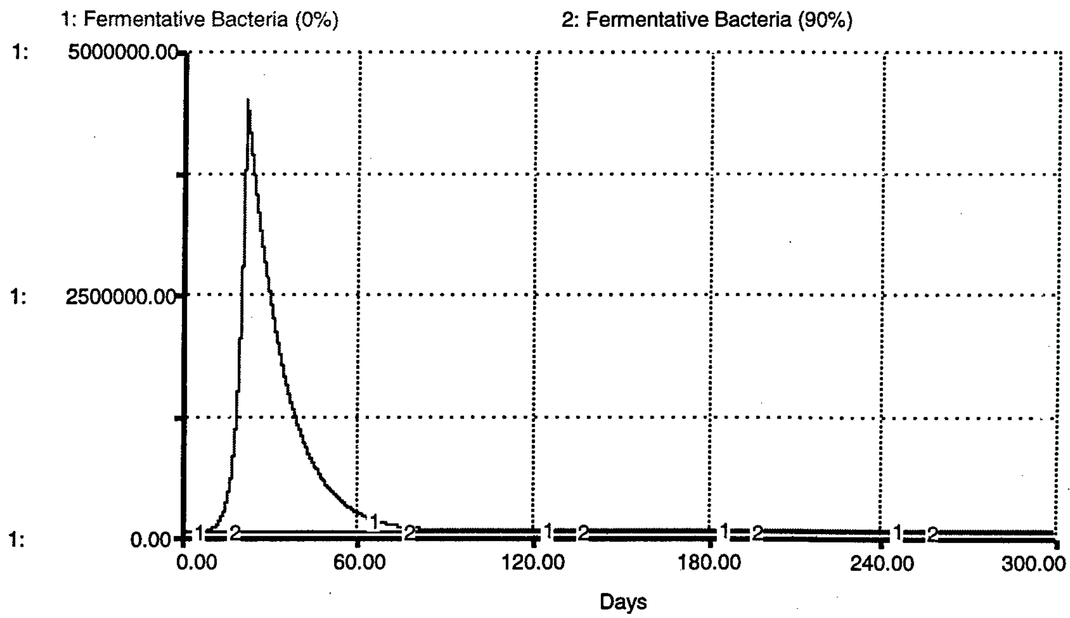


Figure 29. Fermentative Bacteria Growth Under Extreme Waste Sphere Maximum Moisture Conditions

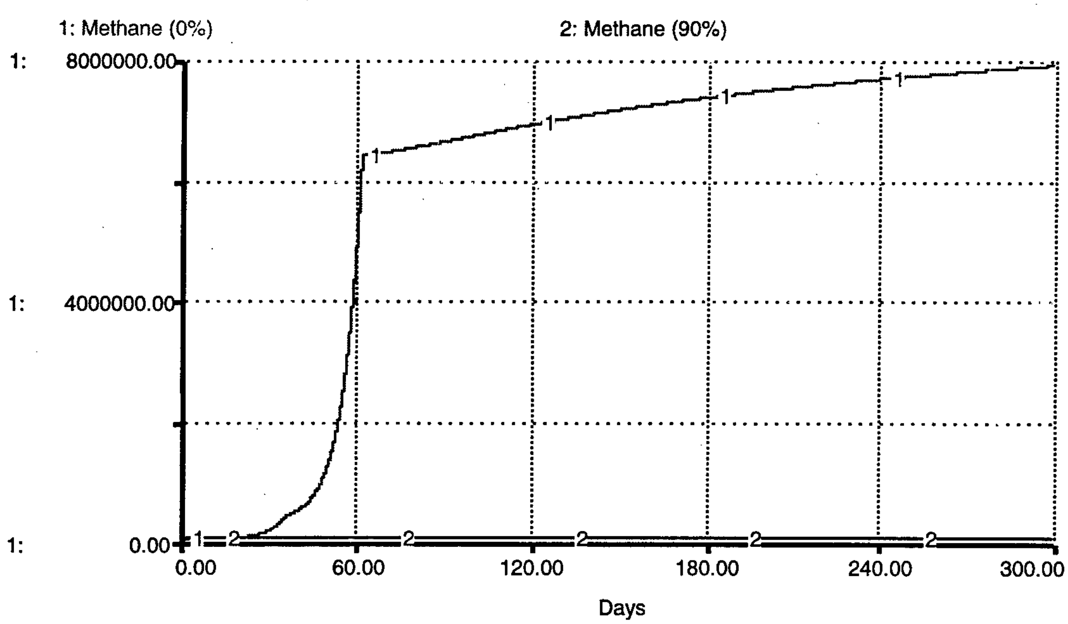


Figure 30. Methane Generated Under Extreme Waste Sphere Maximum Moisture Conditions

Percent Moisture. The Extreme Conditions Test showed that changing percent moisture from the low extreme to the high extreme accelerated bacterial growth and methane generation. Percent moisture values of 10, 20, 30, 40, and 50 percent were used to reveal the sensitivity of the model between the two extremes. Acetogenic Bacteria Growth and Organic Waste Degradation were used to illustrate the behavioral changes. Figures 31 and 32 show the effects of the increasing percent moisture values. As expected, bacteria growth and organic waste degradation are accelerated and increased with increasing initial percent moisture.

Waste Sphere Maximum Moisture. The Waste Sphere Maximum Moisture values used for the Sensitivity Test were 20, 40, 60, and 80 percent. Methanogenic Bacteria and Total Methane Generated were used to represent the behavioral changes. Figures 33 and 34 illustrate that increasing waste sphere maximum moisture slows down and decreases bacterial growth and methane generation. These are the same results as the Extreme Conditions Test. The reasoning for this behavior is discussed in the Extreme Conditions section.

Boundary Adequacy Test. This test determines whether or not the model includes all relevant structure needed to address the model's scope and purpose. The purpose of this research was to determine how landfill parameters and conditions affect solid waste moisture content and explore the effect of moisture content on the degradative processes within the "wet-cell" landfill.

The first part of this purpose statement was addressed by the addition of structure that specifically accounted for the waste sphere maximum moisture and moisture in the void spaces. The second part of the purpose statement was addressed by the modification

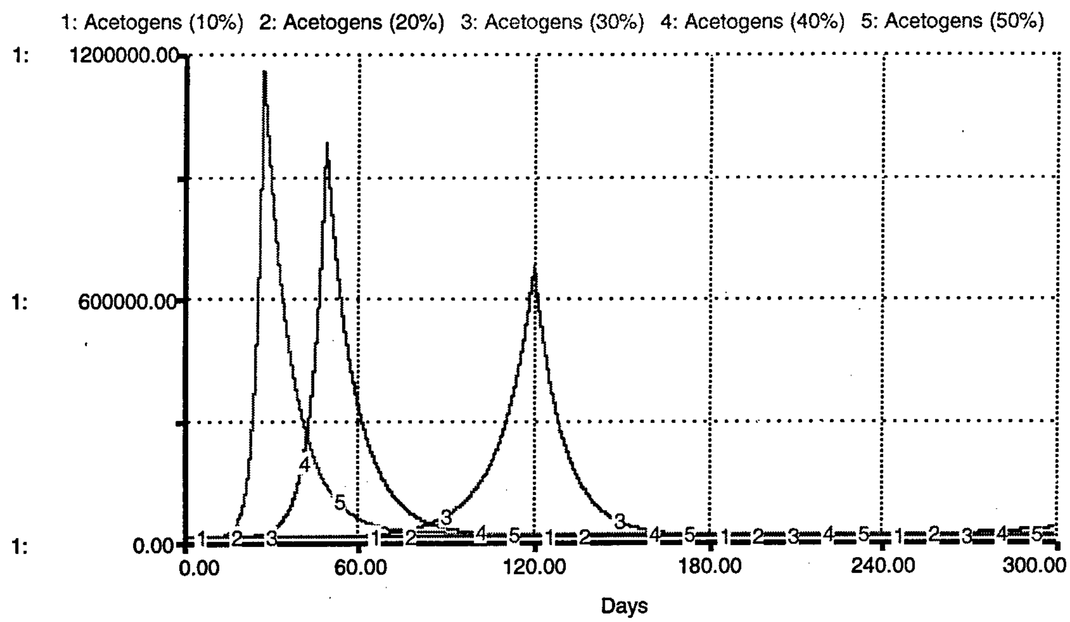


Figure 31. Acetogen Growth Sensitivity to Changes in Initial Percent Moisture

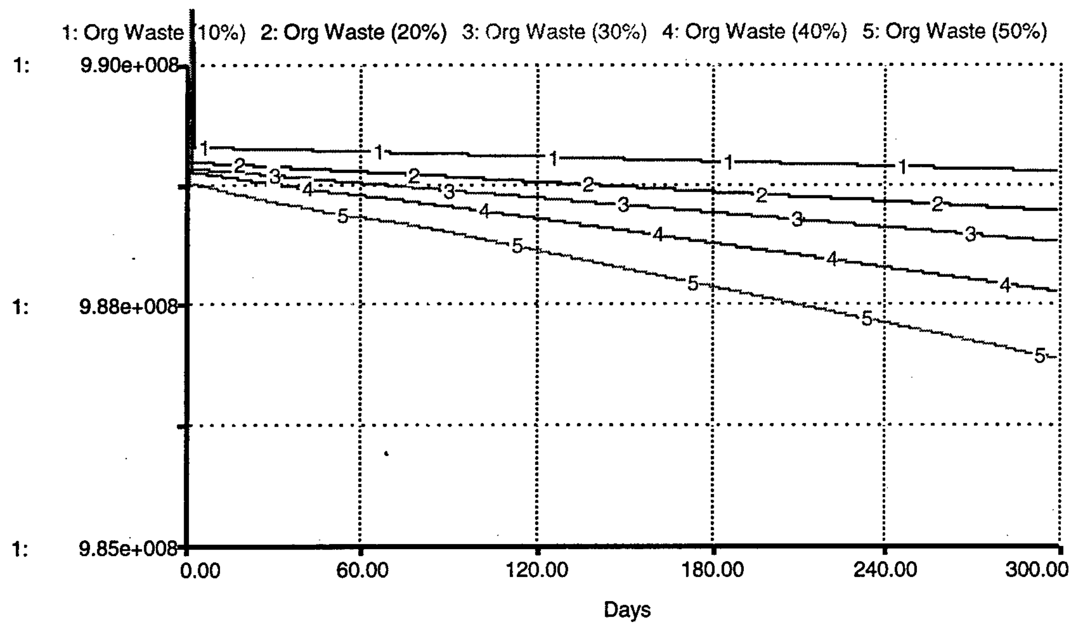


Figure 32. Organic Waste Degradation Sensitivity to Changes in Initial Percent Moisture

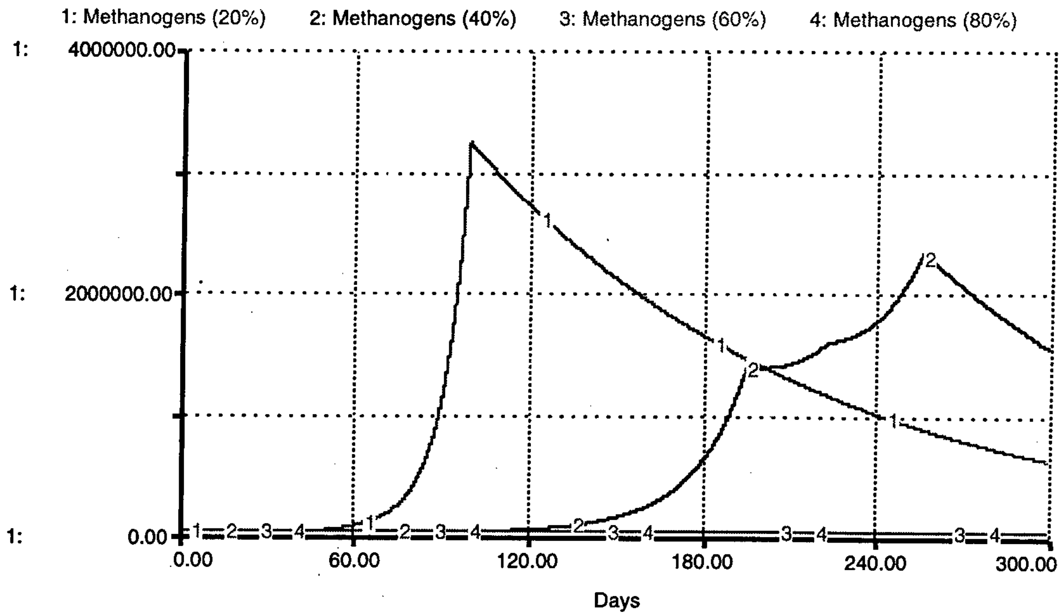


Figure 33. Methanogenic Growth Sensitivity to Changes in Waste Sphere Maximum Moisture

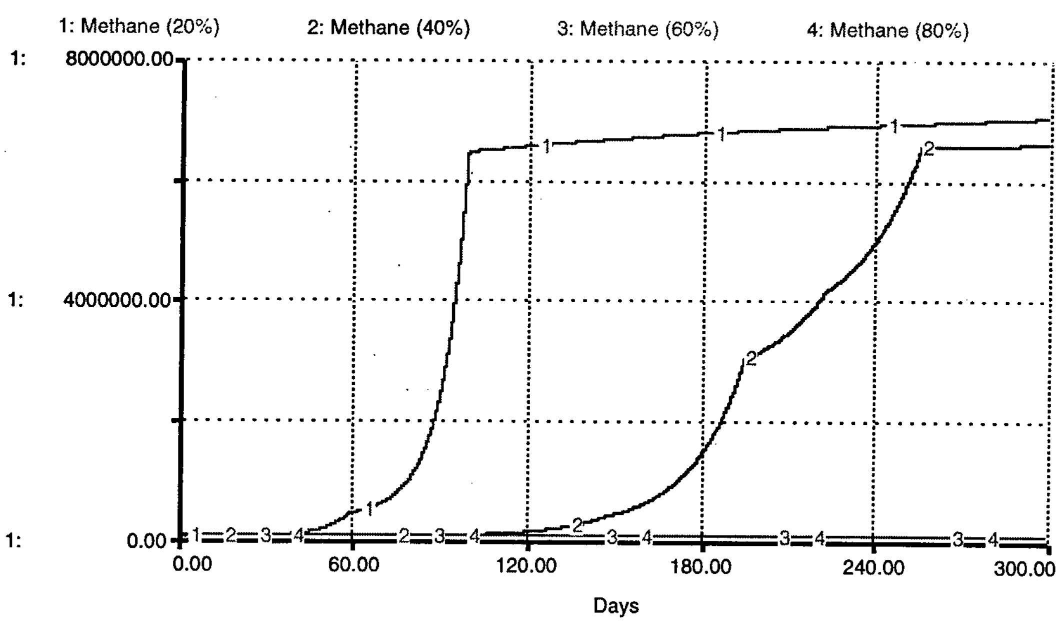


Figure 34. Methane Generation Sensitivity to Changes in Waste Sphere Maximum Moisture

of the moisture factor to account for a broad range of moisture conditions. The moisture factor was graphically scaled according to these moisture conditions to realistically impact bacteria growth and hydrolysis rate.

After review of the completed model by advisors, it was determined that the improved model adequately addresses the model's scope and purpose. Therefore, it passes this test.

Formulation of Leachate and Moisture Infiltration Flow

After successful testing of the initial changes and additions to the model, additional structure was again added to the model. This added structure is shown in the flow diagram in Figure 35. The moisture stock flow diagram will continue to have the two inflows and two outflows used in the Colborn and Benter models to represent moisture produced and consumed during the biodegradation processes. However, one outflow (leachate) and one inflow (moisture infiltration) were added to the moisture stock structure. These two flows will better represent the "wet-cell" landfill concept. Leachate flow was added first and tested to determine its impact on the model. After this testing, moisture infiltration flow was incorporated into the model and tested.

Figures 36 and 37 show the graphical functions that were used to represent leachate collection and moisture infiltration rates, respectively. The leachate collection and moisture infiltration rates were taken from relevant literature detailing previous landfill bioreactor studies using moisture addition or leachate recycle. The leachate collection rate graphical function uses percent moisture in the voids as the independent variable. It starts at zero when no moisture is in the voids and increases to a maximum value of 0.25 percent flow rate per day (based on organic waste mass) at saturation.

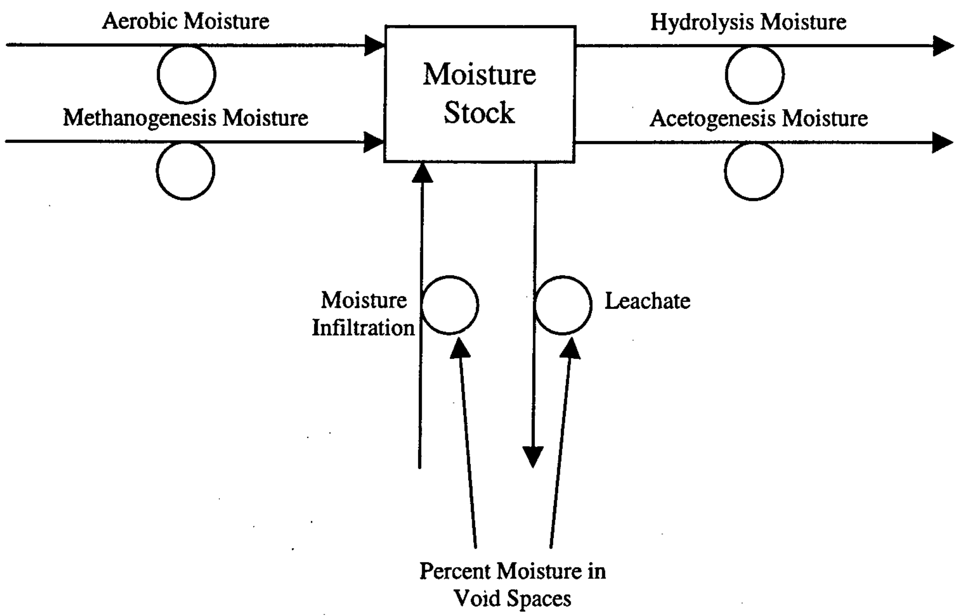


Figure 35. Generic Flow Diagram for Moisture Flow

The moisture infiltration rate graphical function also uses percent moisture in the voids as the independent variable. The daily recirculation rates from most of the studies ranged from 0.002 to 0.05 mass units of moisture for each mass unit of waste in the test cell (Reinhart and Townsend, 1998: 32-45). This translates to a 0.2-5 percent flow rate per day based on organic waste mass. The water infiltration rate for this model is based on a graphical function using percent moisture in the voids as the independent variable. The moisture infiltration graphical function has a maximum flow rate of one percent moisture per day (based on organic waste mass) when no moisture is in the void spaces and a low of zero near complete saturation. The flow drops to zero at 90 percent moisture in the void spaces, instead of at 100 percent, because this provides for a "cushion" to prevent unneeded water flow into the landfill when it is completely saturated. The flow rate values fall within the range used by previous real system studies.

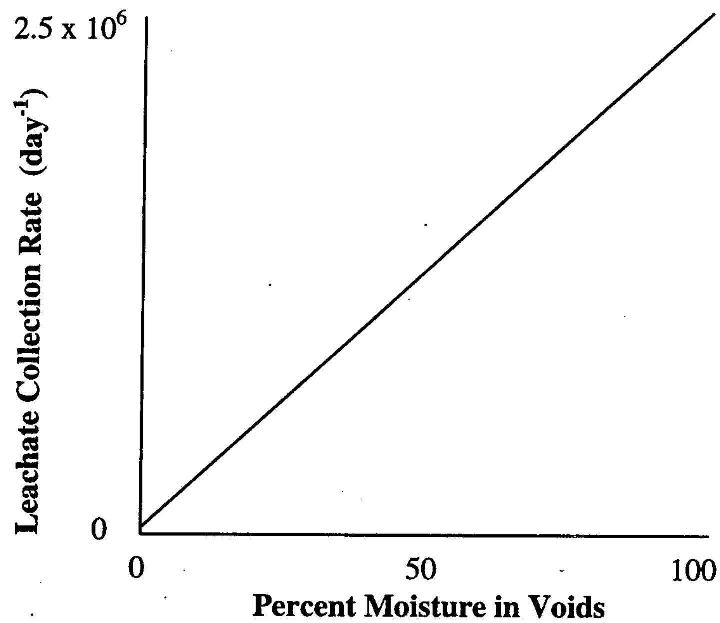


Figure 36. Graphical Function for Leachate Collection Rate

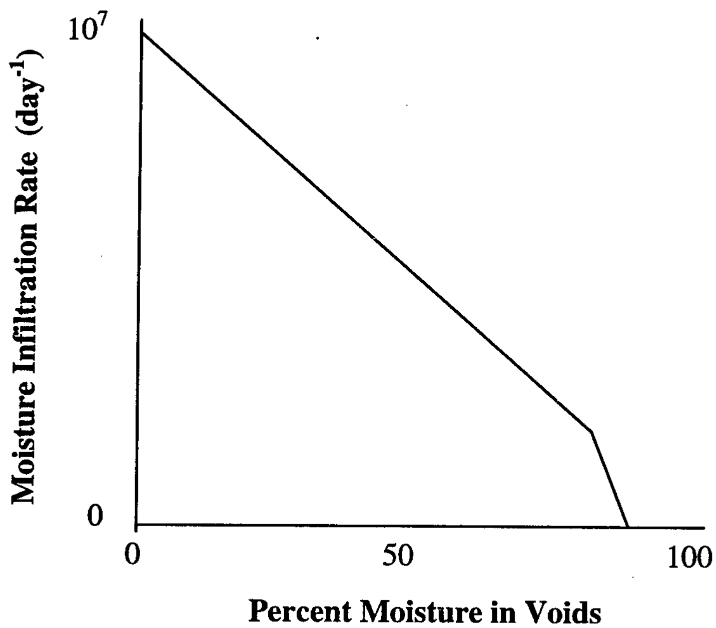


Figure 37. Graphical Function for Moisture Infiltration Rate

Testing Leachate and Moisture Infiltration Flow

Testing Leachate Flow. As stated before, leachate flow was added to the model first. Simulations were run with this new flow structure to compare it to the basic model previously tested. Figure 38 shows the basic gas fraction output of the model using initial conditions with the added leachate flow. These initial conditions are 25 percent moisture content and 35 percent waste sphere maximum moisture.

Comparing Figure 38 to the original model basic output in Figure 21 shows that there was no change to the gas fractions. This was expected. There was no change because, although the leachate structure was added, leachate flow was zero. Leachate flow was zero because waste moisture conditions did not exceed the waste sphere maximum moisture and moisture did not flow into the void spaces. A better representation of the impact of leachate flow will be illustrated in the extreme

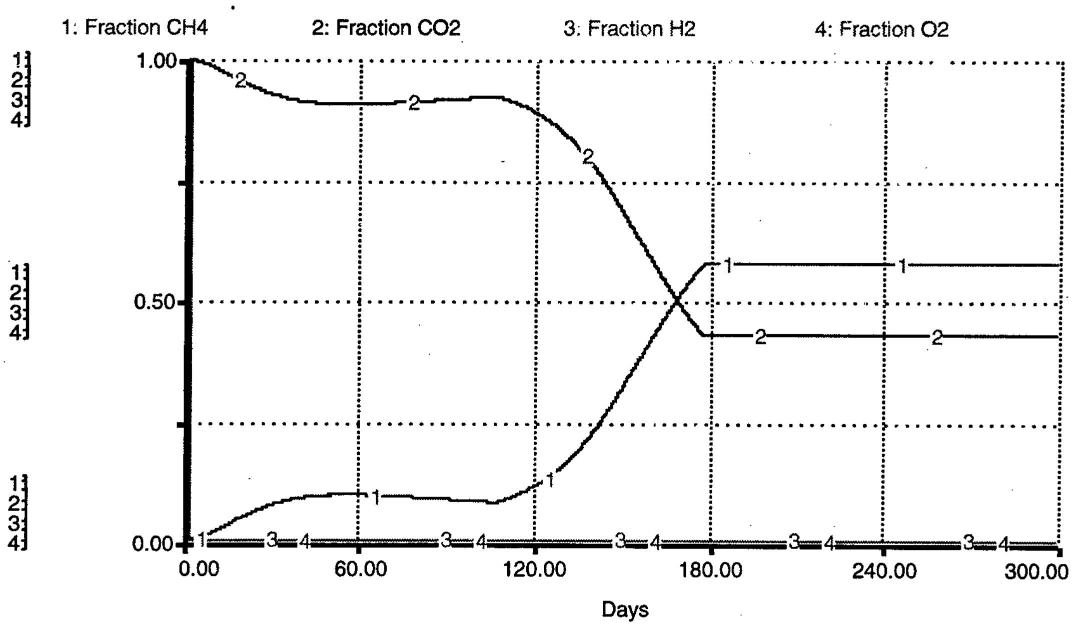


Figure 38. Basic Output of Model with Leachate Flow

conditions and sensitivity tests when moisture content and waste sphere maximum moisture are changed.

Structure Verification. The leachate flow was added to the moisture stock based on the influence diagram in Figure 14. This section of the influence diagram was based on a review of operating and test landfills, a literature review, and discussions with advisors. Since this structure is actually present in operating landfills, it is assumed valid and realistic.

Parameter Verification. The parameter values used for leachate flow were within the ranges mentioned in the literature for experimental bioreactor landfills. Therefore, the parameters are assumed to be valid.

Extreme Conditions Test. Extreme conditions for leachate flow rates were not tested because they would have had no impact on the model using initial conditions. However, tests were conducted on the impact of leachate flow using extreme conditions of percent moisture and waste sphere maximum moisture. Changing these two variables to simulate percent moisture greater than waste sphere maximum moisture caused leachate flow to impact the model.

Percent Moisture. Extreme percent moisture values of zero and 55 percent were used to illustrate model behavior with the leachate flow. Figure 39 is the behavior of the gas fraction for maximum percent moisture (saturated) conditions with leachate flow. This graph is very similar to the gas fraction for saturated conditions without leachate flow (Figure 24). The main difference between the two graphs is that Figure 39 goes to equilibrium sooner but at a lower methane gas fraction. This is because moisture is leaving the system though the leachate outflow and moisture conditions are falling below optimum.

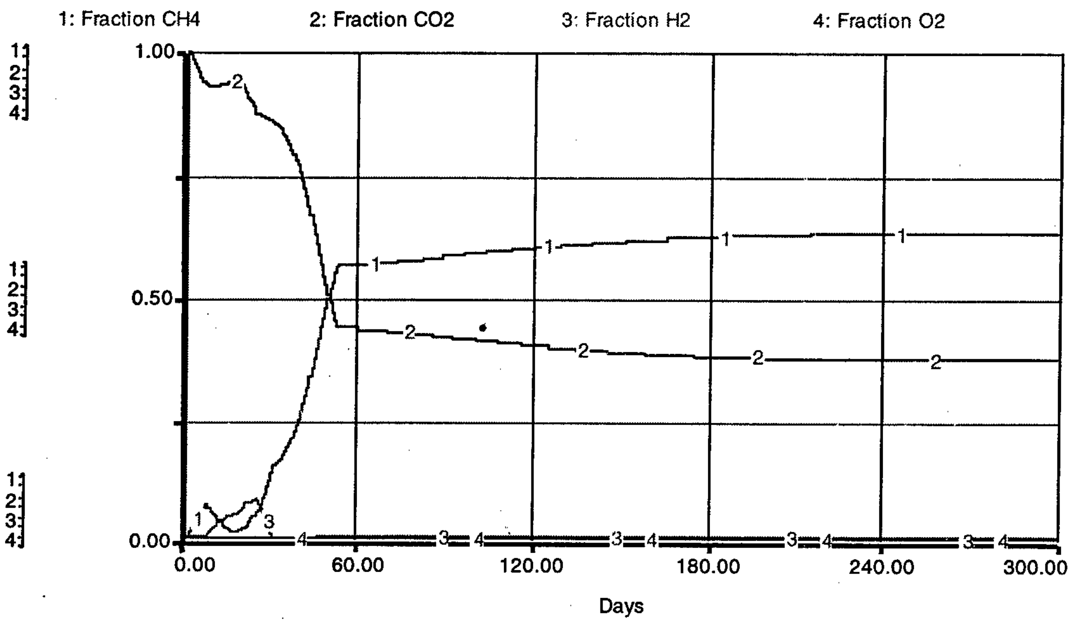


Figure 39. Gas Fraction with Leachate Flow Under Extreme Percent Moisture Conditions (Saturated)

Figures 40 and 41 show the impact of extreme percent moisture values on methanogenic bacteria growth and methane generation, respectively. Trace 1 for both graphs shows the results when percent moisture is zero percent. Trace 2 is percent moisture at 55 percent or fully saturated. Trace 3 is the results from 55 percent moisture without leachate flow. Trace 3 is included as a comparison to visualize the impact of leachate flow on the system. Both Figures 40 and 41 show that leachate flow at saturation takes time to impact the system. A trace illustrating the impact of leachate flow at zero percent moisture content was not included because it would have been the same as Trace 1.

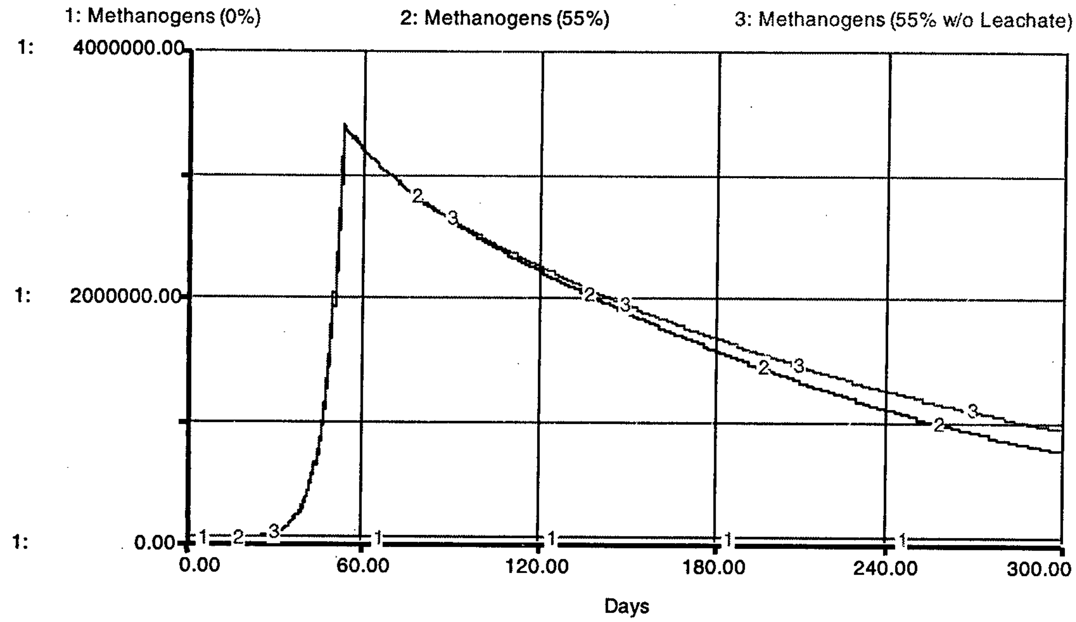


Figure 40. Methanogen Growth with Leachate Flow Under Extreme Percent Moisture Conditions

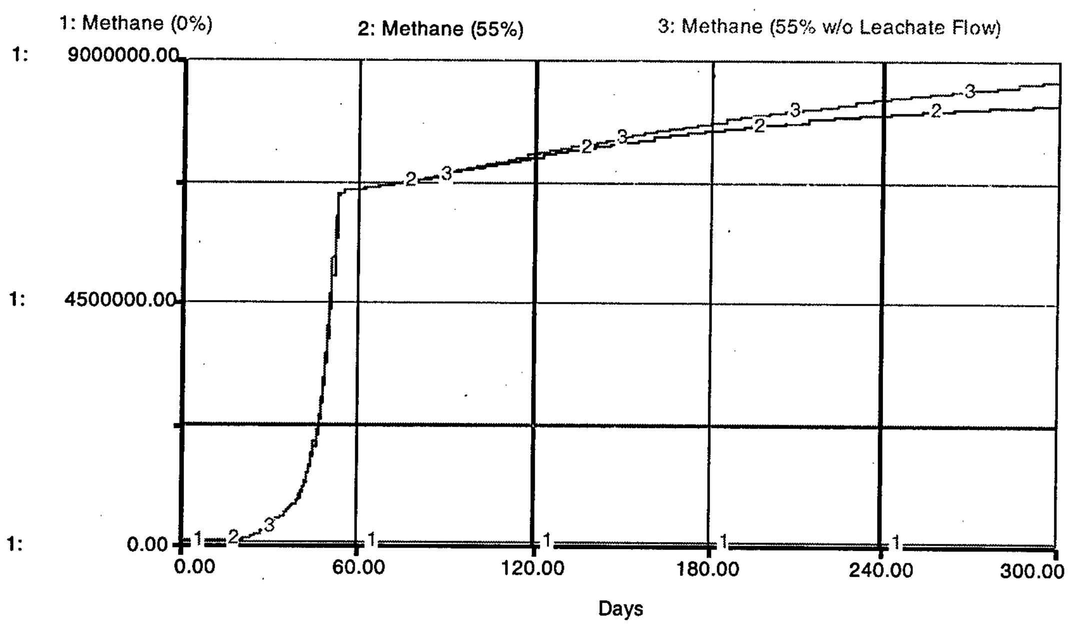


Figure 41. Methane Generated with Leachate Flow Under Extreme Percent Moisture Conditions

Waste Sphere Maximum Moisture. Extreme values of zero and 90 percent waste sphere maximum moisture were used to illustrate model behavior with the leachate flow. Figure 42 shows the behavior of the gas fraction at zero percent waste sphere maximum moisture with leachate flow. The gas fraction graph is similar to the gas fraction curve without leachate flow (Figure 27). However, there is a slightly noticeable slow down of gas generation in the graph with leachate flow.

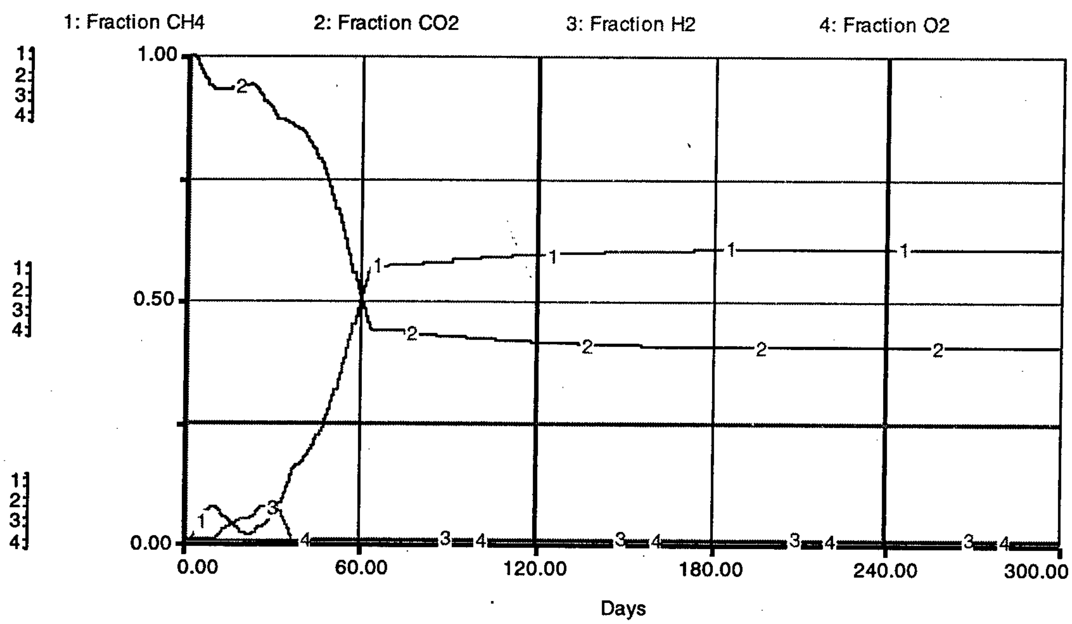


Figure 42. Gas Fraction with Leachate Flow Under Extreme Waste Sphere Maximum Moisture Conditions (Zero Percent)

Figures 43 and 44 illustrate the impact of extreme waste sphere maximum moisture values on fermentative bacteria growth and methane generation, respectively. Trace 1 for both graphs shows the results when waste sphere maximum moisture is zero percent. Trace 2 is waste sphere maximum moisture at 90 percent. Trace 3 is the results from zero percent waste sphere maximum moisture without leachate flow. Trace 3 is included as a comparison to better visualize the impact of leachate flow on the system. Figures 43 shows that leachate flow has a very limited impact on fermentative bacteria population. This is because fermentative bacteria reach their population peak before the leachate flow has considerably impacted the moisture content and decreased moisture conditions below optimum. Unlike fermentative bacteria growth, long-term methane generation in Figure 44 is impacted by the leachate flow. A trace illustrating no leachate flow at 90 percent waste sphere maximum moisture was not included because it would have been the same as Trace 2.

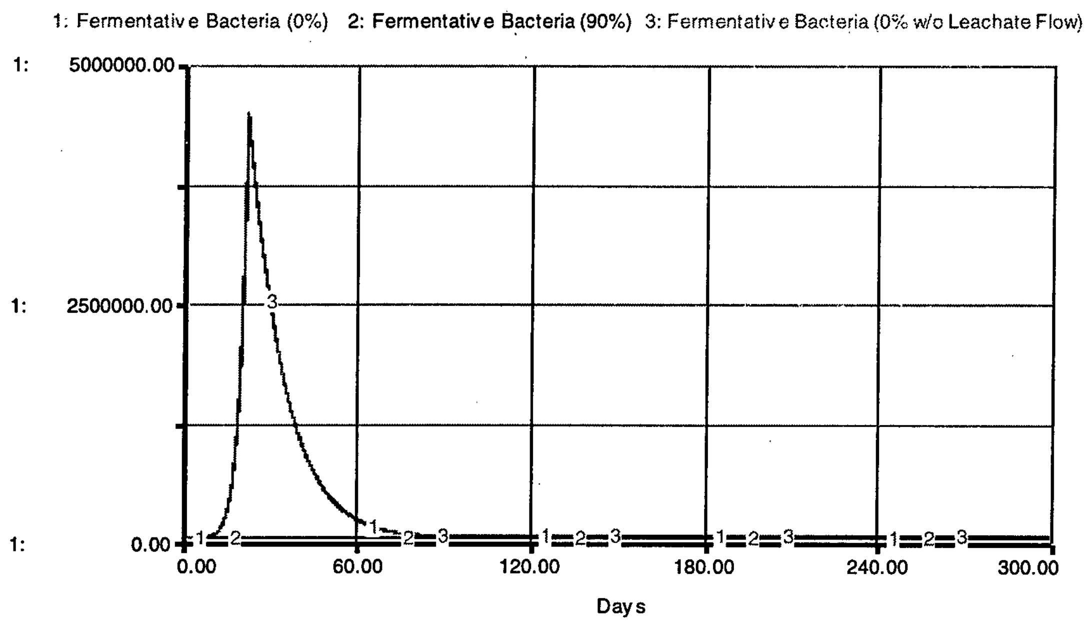


Figure 43. Fermentative Bacteria Growth with Leachate Flow Under Extreme Waste Sphere Maximum Moisture Conditions

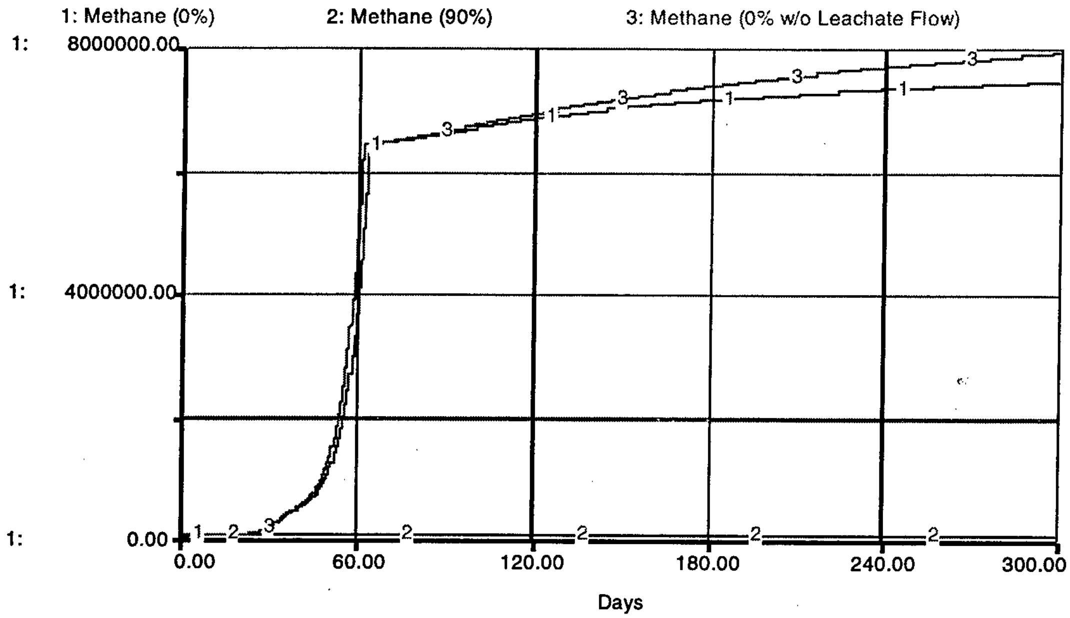


Figure 44. Methane Generated with Leachate Flow Under Extreme Waste Sphere Maximum Moisture Conditions

<u>Sensitivity Test</u>. Like the extreme conditions test, the sensitivity test was conducted by changing the values of percent moisture and waste sphere maximum moisture. These tests illustrated what impact leachate flow had on various criteria over a range of values for percent moisture and waste sphere maximum moisture. Only one criteria for each variable was tested because the extreme conditions tests indicated that leachate flow has a limited impact on bacterial growth and methane generation when compared to no leachate flow.

<u>Percent Moisture</u>. Percent moisture values of 10, 20, 30, 40, and 50 percent were used to reveal the sensitivity of the model between the two extremes. Acetogenic Bacteria Growth was used to illustrate the behavioral changes. Figures 45 show the effects of the increasing percent moisture values. As expected, bacteria growth

and organic waste degradation are accelerated and increased with increasing initial percent moisture.

Waste Sphere Maximum Moisture. The Waste Sphere Maximum Moisture values used for the Sensitivity Test were 20, 40, 60, and 80 percent. Total Methane Generated was used to represent the behavioral changes. Figure 46 illustrates that increasing waste sphere maximum moisture slows down and decreases bacterial growth and methane generation. These are the same results as the Extreme Conditions Test. The reasoning for this behavior is discussed in the Extreme Conditions section.

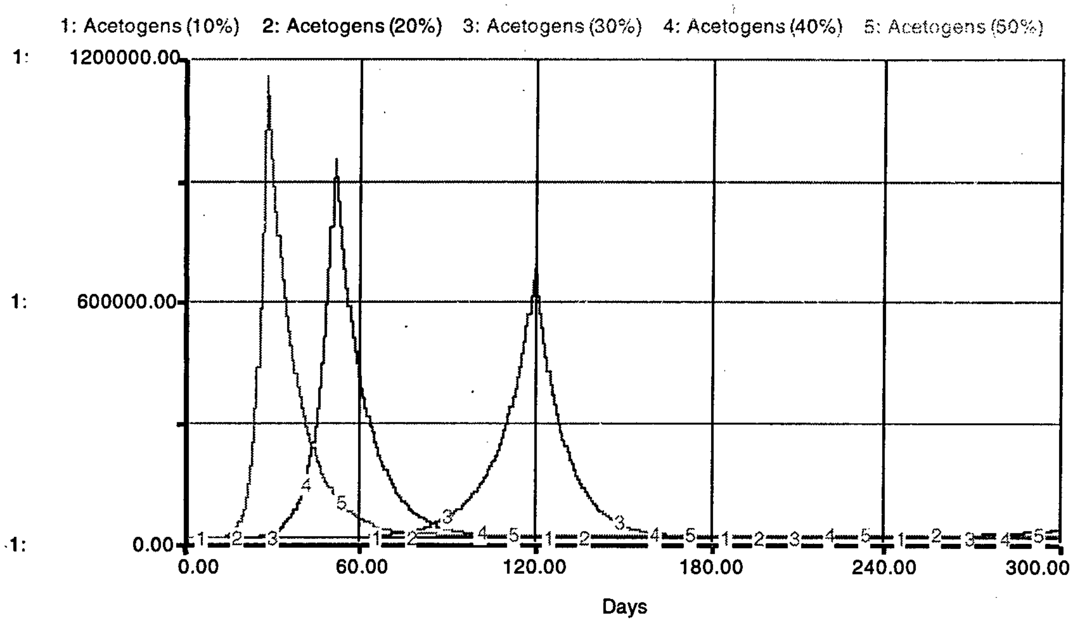


Figure 45. Acetogen Growth Sensitivity to Changes in Percent Moisture with Leachate Flow

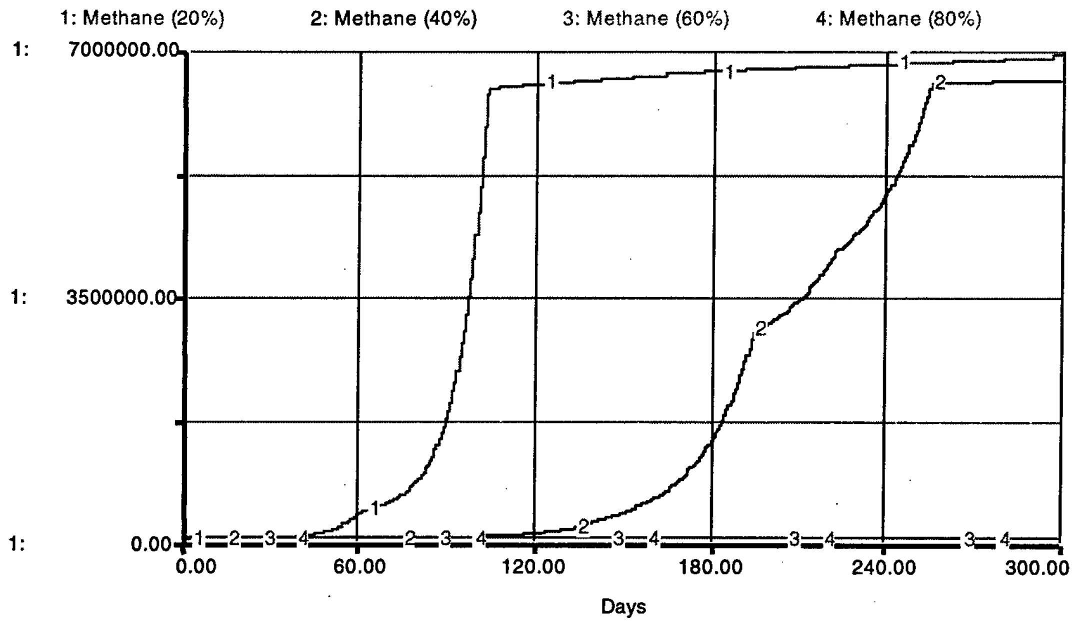


Figure 46. Methane Generation Sensitivity to Changes in Waste Sphere Maximum Moisture with Leachate Flow

<u>Testing Moisture Infiltration Flow</u>. Testing of the Moisture Infiltration Flow Structure will follow the same pattern as the testing for the percent moisture and waste sphere maximum moisture variables. For the extreme conditions and sensitivity tests, different flow rates will be introduced into the model and simulations run to determine and illustrate any changes caused by the moisture infiltration flow.

Figure 47 shows the basic gas fraction output of the model using initial conditions with leachate flow and the added moisture infiltration flow. These initial conditions are 25 percent moisture content, 35 percent waste sphere maximum moisture, and leachate and moisture infiltration flow rates as shown in Figures 36 and 37.

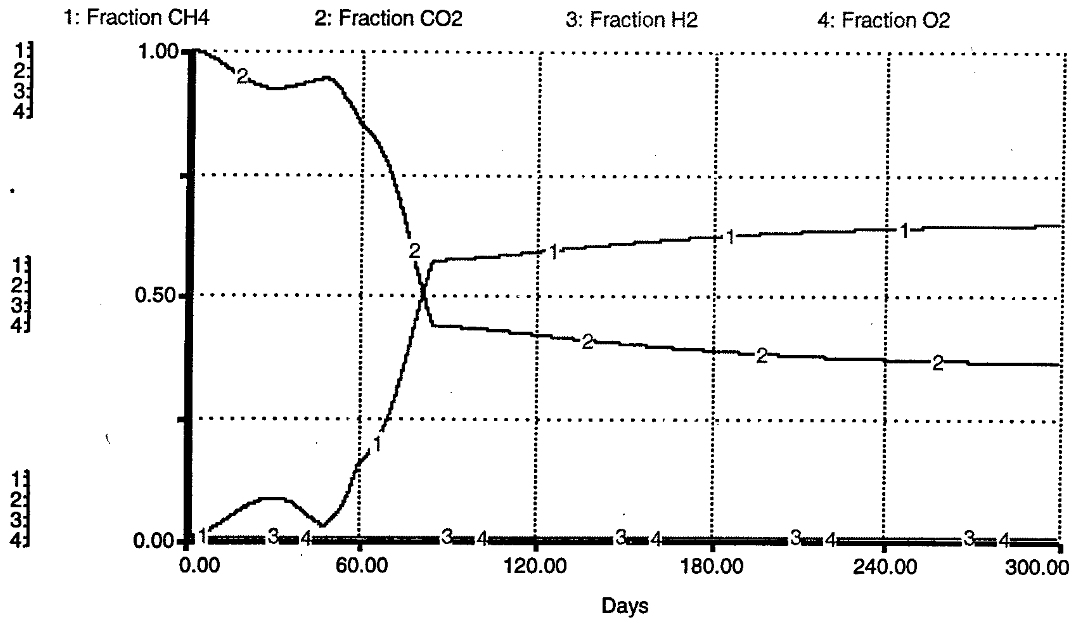


Figure 47. Basic Output of Model with Leachate and Moisture Infiltration Flow

Comparing Figure 47 to the original model basic output in Figure 21 and the leachate basic output in Figure 38 shows a dramatic acceleration in the gas generation processes. This was expected. Adding moisture to the system increases the moisture content to near optimum conditions.

Figure 48 is included to illustrate the moisture variable values with leachate and moisture infiltration flow. The maximum percent moisture allowable in the system remains at approximately 55 percent. The percent moisture in the total system starts at 25 percent and rises to about 53 percent due to the moisture infiltration. Also, percent moisture in the voids begins to rise at about Day 25 and continues to rise to 80 percent because the percent moisture in the system exceeds the waste sphere maximum moisture.

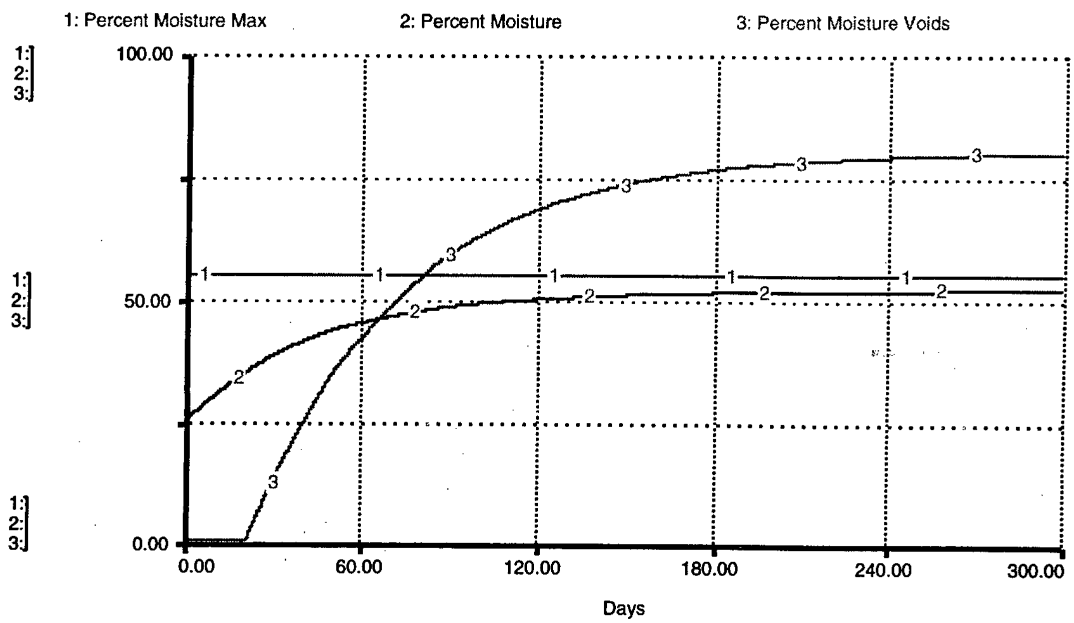


Figure 48. Moisture Variable Values with Leachate and Moisture Infiltration Flow

Structure Verification Test. The moisture infiltration flow was added to the moisture stock based on the influence diagram in Figure 14. This section of the influence diagram was based on a review of operating and test landfills, a literature review, and discussions with advisors. Since this structure is actually present in operating landfills, it is assumed valid and realistic.

Parameter Verification Test. The moisture infiltration rate was taken from literature detailing previous landfill bioreactor studies using normal water addition or leachate recycle. The flow rate values shown in Figure 37 fall within the range used by previous real system studies. Therefore, the parameters are assumed to be valid.

Extreme Conditions Test. To test behavior under extreme conditions for moisture infiltration flow rate, two different flow rates were introduced into the model. These extreme rates are zero and ten times the original flow rate. Figures 49 and 50 illustrate the effects of these two flow rates on organic waste degradation and methane generation. Trace 1 utilizes a flow rate of zero, trace 2 utilizes the original flow rate, and trace 3 utilizes a flow rate ten times the original flow rate. The original flow rate is included as a comparison. It is expected that increased flow rate will lead to faster organic waste degradation and higher methane generation. This is due to moisture conditions reaching optimal values sooner. In the case of zero moisture infiltration flow, moisture conditions may never reach optimal values.

Both figures illustrate that an increased daily flow of moisture does accelerate organic waste degradation and methane generation. However, if the maximum flow rate is used in real life, the gains in waste degradation and methane generation may be overshadowed by the increase in leachate flow, both through the leachate collection system and vertically up through the waste. Therefore, care must be taken in choosing a flow rate because real system conditions and limitations must guide the rate.

Sensitivity Test. The Moisture Infiltration Flow Rate values used for the Sensitivity Test were 0.5, 2, 4, and 8 times the original flow value. Acetogenic Bacteria and Total Methane Generated were used to represent the behavioral changes. Figure 51 and 52 illustrate the effects of the increasing Moisture Infiltration Flow Rate. As expected, an increased rate yields quicker and greater bacteria growth and total methane generation.

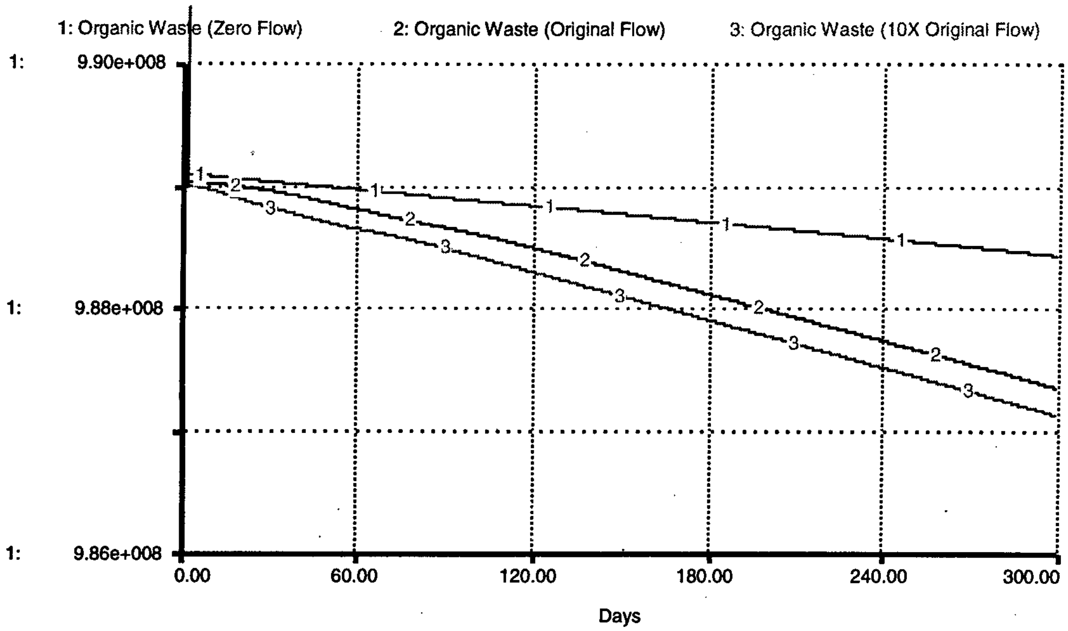


Figure 49. Organic Waste Degradation Under Extreme Moisture Infiltration Flow Conditions

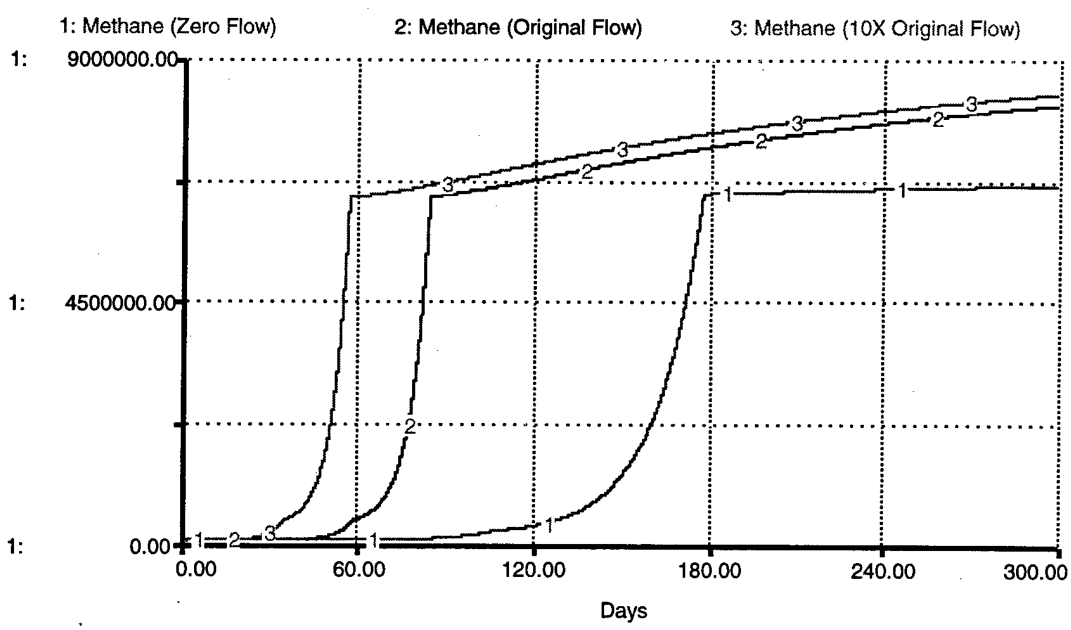


Figure 50. Methane Generation Under Extreme Moisture Infiltration Flow Conditions

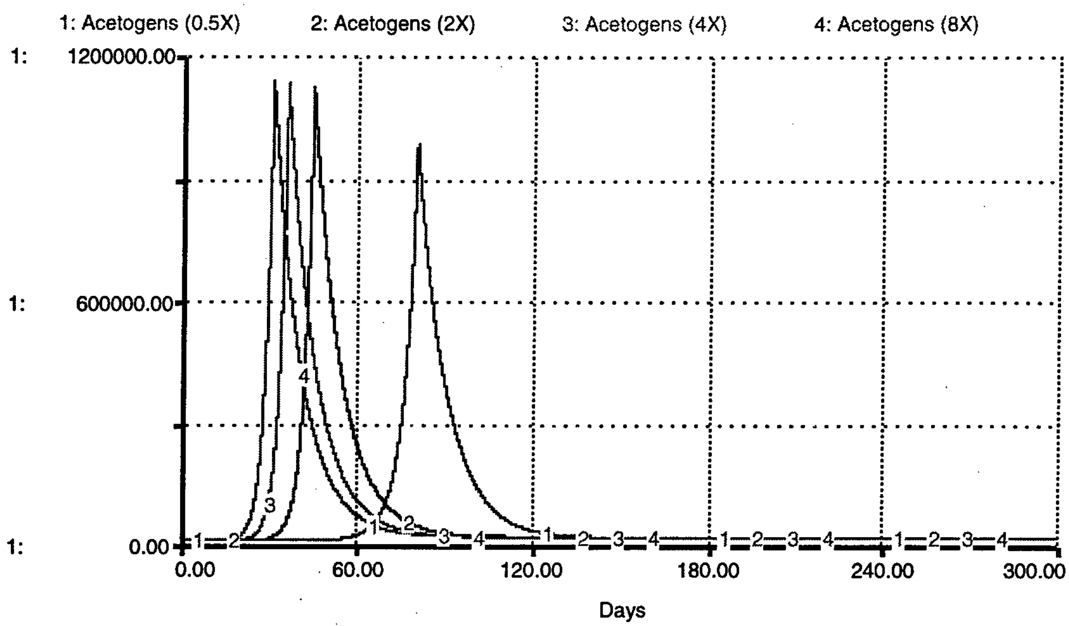


Figure 51. Acetogenic Bacteria Sensitivity to Changes in Moisture Infiltration Flow Rate

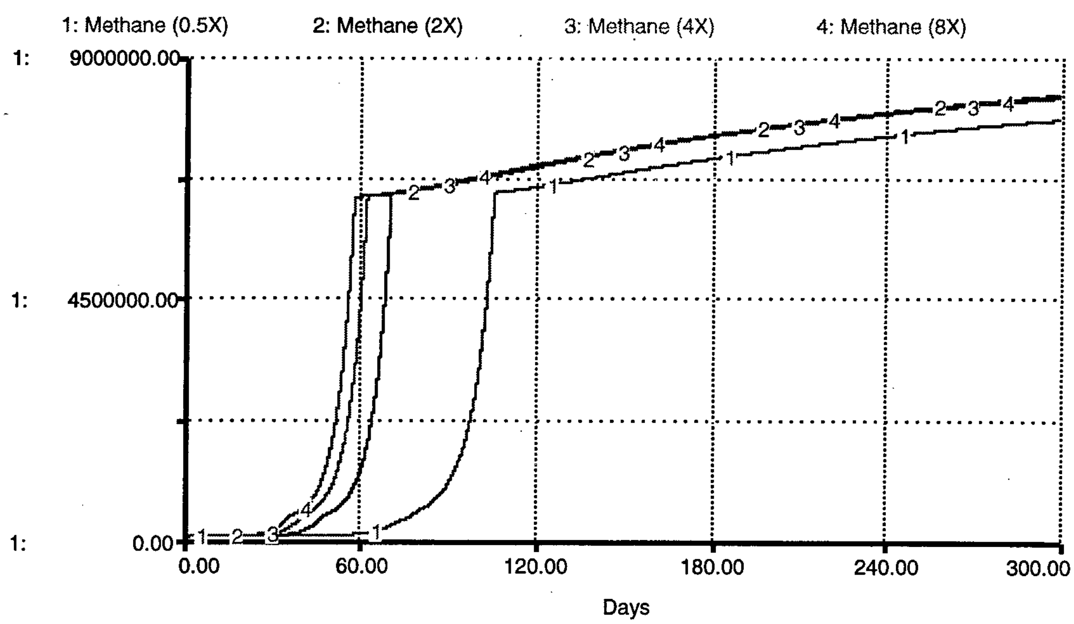


Figure 52. Total Methane Generation Rate Sensitivity to Changes in Moisture Infiltration Flow Rate

Implementation

The implementation stage for this research consist of three example model runs to simulate how the model could be implemented in the field to aid the landfill management process. Parameters and conditions in the model were changed and recommendations made about how a landfill manager could change inputs (e.g. pre-wetting waste to increase initial moisture content) to optimize biodegradation and methane generation based on these conditions and parameters. Total methane generated was used as the metric for all three examples. Table 3 shows all the parameter values and how they were changed to determine the best conditions to optimize methane generation.

Table 3. Parameter Values for Implementation Examples

	Example 1	**Example 2**	**Example 3**
Initial Percent Moisture	15%	25%	35%
Waste Sphere Max Moisture	35%	55%	45%
Leachate Flow Rate	Same as Initial Model Conditions	Same as Initial Model Conditions	Same as Initial Model Conditions
Moisture Infiltration Flow Rate	Same as Initial Model Conditions	Same as Initial Model Conditions	Same as Initial Model Conditions
Trace 1	Above Conditions	Above Conditions	Above Conditions
Trace 2	Increase Initial Percent Moisture to 30%	Increase Initial Percent Moisture to 30%	Increase Initial Percent Moisture to 45%
Trace 3	Raise Moisture Infiltration Rate 2X	Raise Moisture Infiltration Rate 2X	Raise Moisture Infiltration Rate 2X
Trace 4	Raise Both	Raise Both	Raise Both

<u>Example 1</u>. Figure 53 shows the results of the model simulation using the conditions contained in Table 3 for Example 1. The largest increase in methane generation is from Trace 4. This trace includes increasing both percent moisture and moisture infiltration rate. Traces 2 and 3 increased methane generation about equally. The landfill manager could use this information to determine the best option for increasing methane generation and waste degradation. If the manager possessed the resources, the best option might be the conditions used in Trace 4.

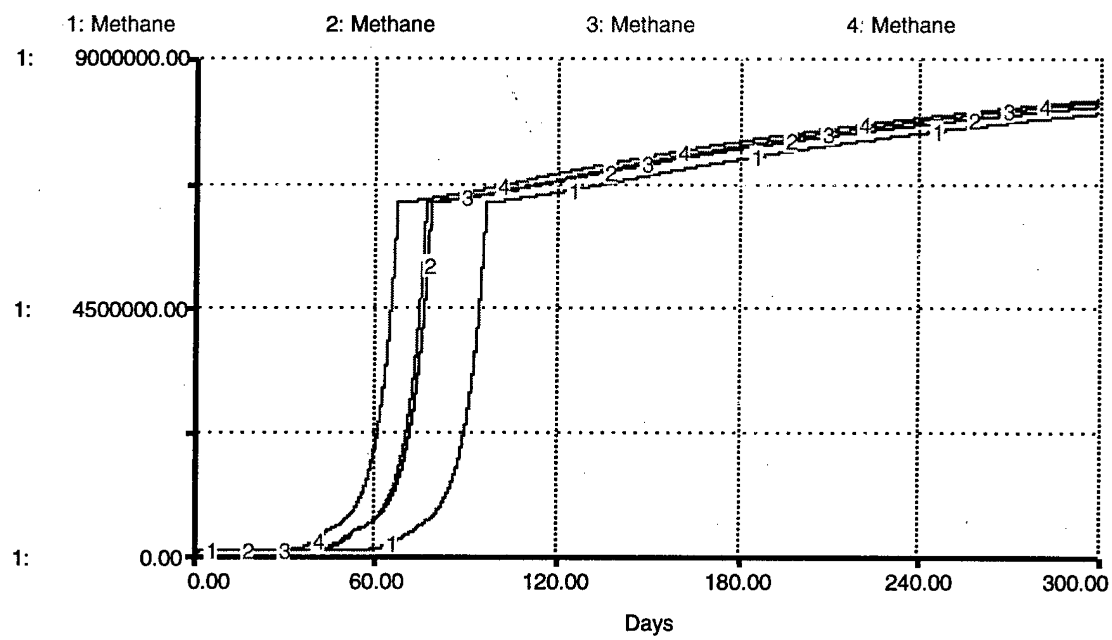


Figure 53. Results of Example 1 Implementation Simulation

<u>Example 2</u>. The results from this example run are illustrated in Figure 54. Based on the initial conditions for Example 2, increasing the percent moisture to 30 percent had a limited impact on methane generation. Increasing moisture infiltration rate, however,

dramatically increases methane generation. If resources allow, increasing moisture infiltration rate would be the best option to increase methane generation for the initial conditions.

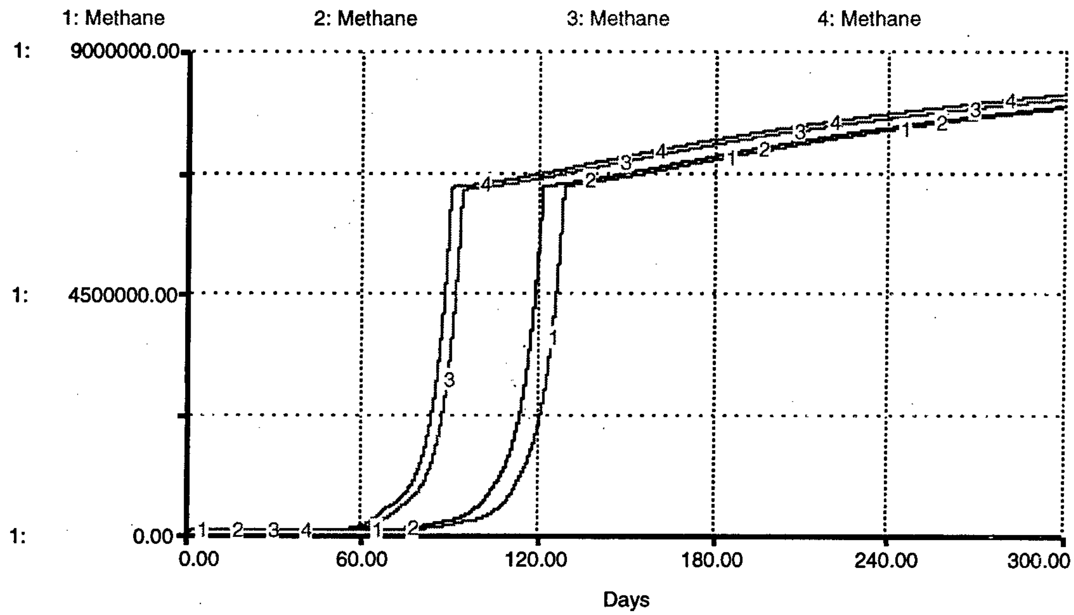


Figure 54. Results of Example 2 Implementation Simulation

Example 3. The results from Example 3 in Figure 55 are similar to Example 1. Increasing percent moisture and moisture infiltration rate each result in about the same increase in methane generation. However, increasing percent moisture from 35 percent to 45 percent would involve a large amount of pre-wetting of the waste. Therefore, the best option for increasing methane generation in this example might be increasing moisture infiltration rate.

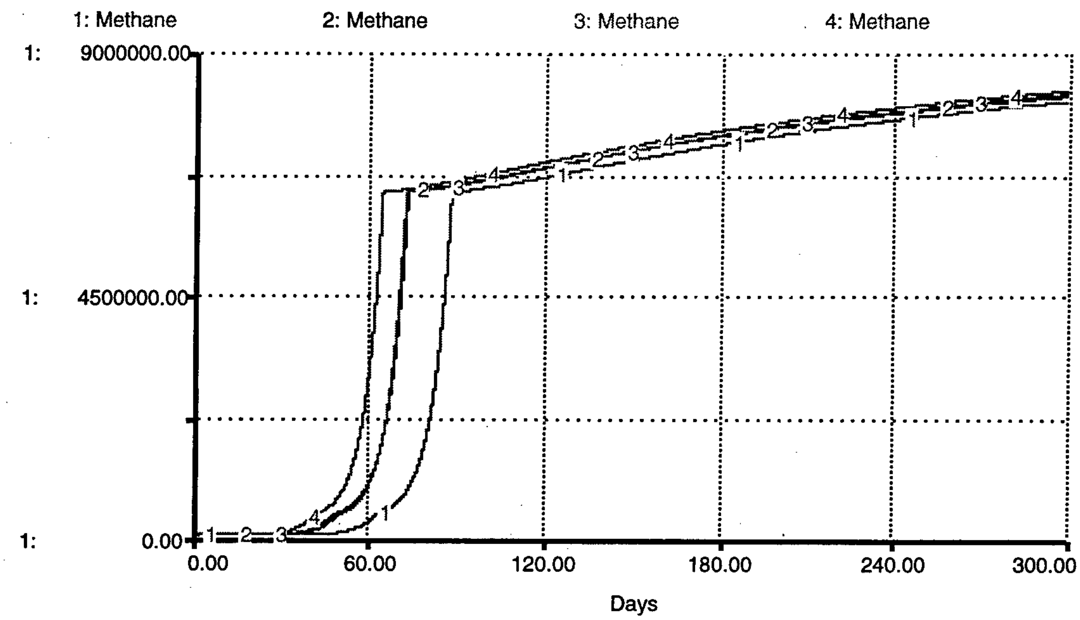


Figure 55. Results of Example 3 Implementation Simulation

These three implementation examples were included as a thumbnail sketch of how the model could perform and what the model could do for a landfill manager. These examples only changed moisture conditions. However, these are not the only parameters that could be changed. The combinations of variables that can be changed to predict landfill behavior are countless.

V. Conclusions and Recommendations for Further Study

Moisture content and availability in a solid waste landfill are among the most important environmental factors affecting waste degradation. The presence or lack of moisture in a landfill can ultimately change the time frame for waste degradation and landfill stabilization from a few years to several decades. Therefore, a model simulating solid waste degradation needs to contain a detailed representation of the behavior and effects of moisture.

The system dynamics model presented here has expanded and improved the representation of moisture contained in the Colborn and Benter models. The boundary of the previous models has been broadened to include the flow of moisture into and out of the system. This new boundary moves the model away from simulating a "dry-tomb" landfill and brings it closer to the "wet-cell" concept of accelerating waste degradation through the manipulation of moisture content. The testing of the new model has confidently shown that the new moisture structure has resulted in plausible behavior in the model and realistically simulated the impacts of moisture content and flow. One major conclusion can be drawn from the testing. To obtain the greatest benefit for waste degradation and gas generation, moisture conditions need to be near optimal, or increased to optimal through moisture infiltration, as early as possible in the degradative processes. The degradative processes are interrelated and have an impact on subsequent processes. If hydrolysis reaches ideal conditions earlier, it will increase and accelerate the availability of substrate for fermentation. This positive relationship follows through all the way to methanogenesis.

Model Strengths

The purpose of this research was to determine how landfill parameters and conditions effect solid waste moisture content and explore the effect of moisture content on the degradative processes within the landfill. The new moisture structure that was added to the model greatly improves the modeling of moisture conditions and more closely represents the "wet-cell" landfill concept. The Colborn and Benter models had generically represented moisture content and its effects. The new model, however, has added structure that allows the model to account for and simulate all moisture conditions from completely dry to completely saturated organic waste.

The model also allows for the simulation of moisture flowing into and out of the system through the addition of leachate and moisture infiltration flows. As demonstrated in the implementation stage in Chapter 4, the model, with the new moisture structure, could be used in the future to manage moisture conditions in a landfill to enhance methane generation.

Model Limitations

No matter how detailed a model becomes, it will never fully and accurately simulate all real system conditions. The first limit to this model originates from the system that is being simulated. A solid waste landfill is extremely heterogeneous, and the contents of the landfill (and the moisture in those contents) are always changing. Although it is not necessarily a weakness or limitation, the parameter values used in the model will never be an exact duplication of the real system.

A possible weakness or limitation in the model is the behavior of hydrogen in the reference mode. As mentioned in the testing stage of the initial moisture structure changes, there is one difference between the basic output and the reference mode that was also present in the Benter model basic output. In the reference mode, the hydrogen fraction increases and peaks before the methane fraction begins an observable increase. However, in this and the Benter model basic outputs, the methane fraction increases before the hydrogen fraction. There is a decrease in methane as hydrogen production increases. However, methane fraction increases again as the hydrogen fraction drops to near zero. The cause of this behavior, both in this model and the Benter model, has not been investigated. Therefore, it has not been determined if the behavior is realistic or an anomaly in the model.

A third limitation to the performance of the model is the representation of landfill gases after they have been generated. In the current model, landfill gases are generated and flow into a stock. There is no outflow from this stock and gases continue to accumulate at the rate that they are generated. The values of these gas stocks are then used to calculate gas fractions, which are used to determine and illustrate the basic output of reference mode diagram. However, in a real solid waste landfill, gases can leave the system in two ways. First, the gases can escape or leak out of the landfill once the pressure inside exceeds atmospheric pressure. Second, gases can be vented from the landfill by creating a vacuum in a gas collection piping system. In addition, the proportions of the various gases exiting the landfill are not strictly dependent on their gas fraction during that point in time. Methane is lighter than air and will tend to vent upward out of a landfill. In contrast, carbon dioxide is denser than air and tends to settle toward the bottom of a landfill. Therefore, the dynamics of the landfill gases need to be addressed to determine their impact on gas movement and the basic output of the reference mode diagram.

Another limitation of the model is the relationship introduced by Benter between aerobic and anaerobic hydrolysis. Benter defines the anaerobic hydrolysis depletion rate as aerobic hydrolysis depletion rate divided by 10,000. This means that anaerobic hydrolysis depletion is 10,000 times less efficient than aerobic hydrolysis depletion. However, some relevant literature has stated that anaerobic hydrolysis depletion is only about 100 times less efficient than aerobic hydrolysis depletion. A more detailed review needs to be conducted to determine the relative relationship of these two variables.

Suggestions for Further Study

For the model to become a useful tool in the management of landfills, there should be further research into its weaknesses and limitations. Some of the limitations of the current model that need to be addressed are:

- Does the new model accurately represent hydrogen gas generation in the reference mode?
- How does the flow of the different landfill gases affect the makeup of the gas fraction in the landfill?
- What is the relative relationship between the aerobic and anaerobic hydrolysis depletion rates?
- How can the model more accurately account for the extreme heterogeneity of the solid waste in a landfill?

Addressing these limitations, and others that may arise during future improvement of the model, will enhance the effectiveness of the model and its use as a landfill management tool.

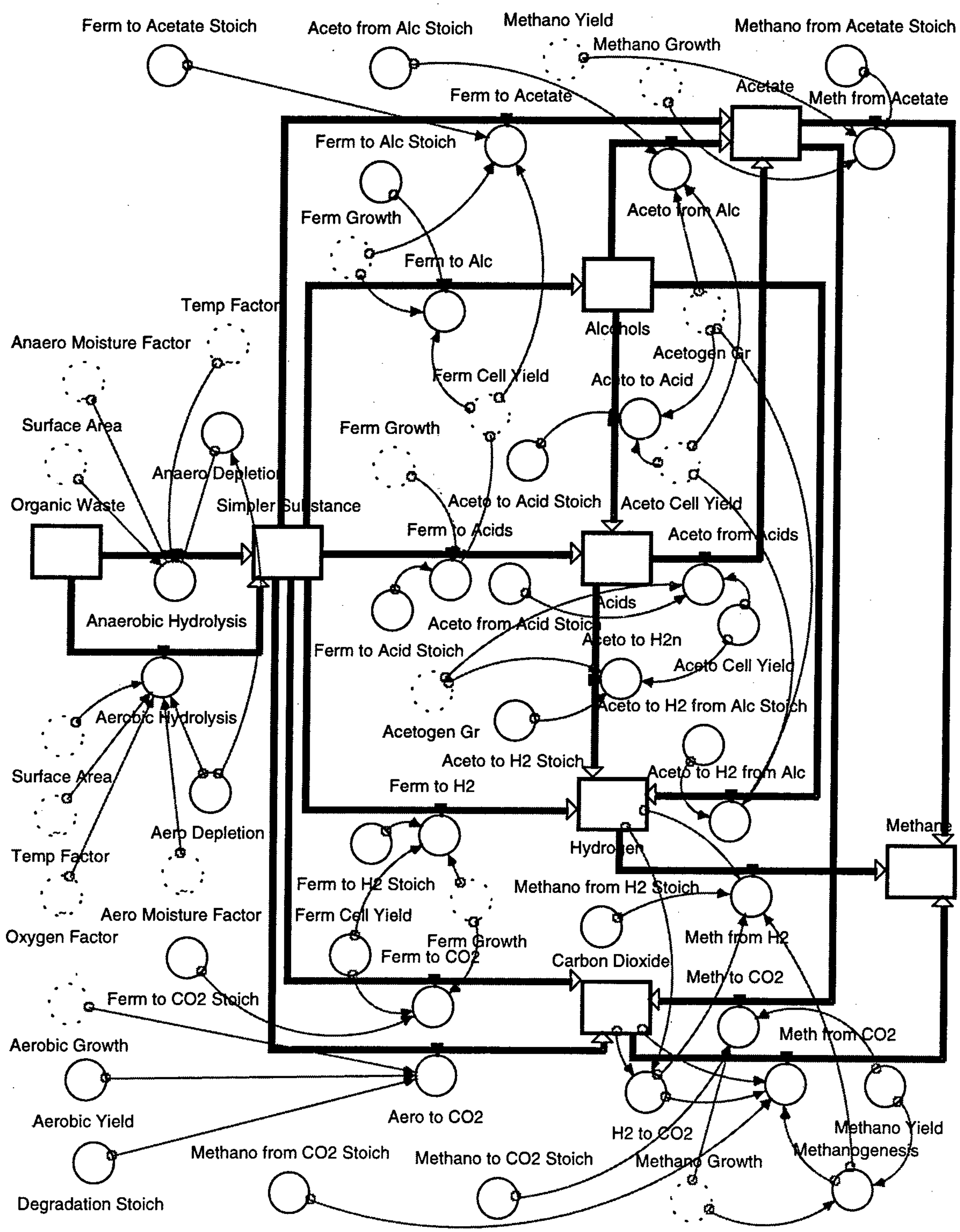
Appendix A: Review of Model Assumptions

- Initial Moisture Content is 25 percent.
- Waste Field Capacity is 45 percent.
- Waste Sphere Maximum Moisture is 35 percent.
- Waste Sphere Maximum Moisture of the organic waste remains constant throughout simulation.
- Water density remains constant at 1000 kg/m^3 throughout simulation.
- Organic waste is present in spheres of radius 0.07 meters. This is a continuation of the Benter assumption.
- The flow of moisture through the waste caused by moisture infiltration and leachate flow does not allow acids to buildup in the waste (lower pH) and negatively affect methanogenesis.
- Both leachate flow and moisture infiltration flow can be managed by the landfill manager based on the percent moisture in the voids.

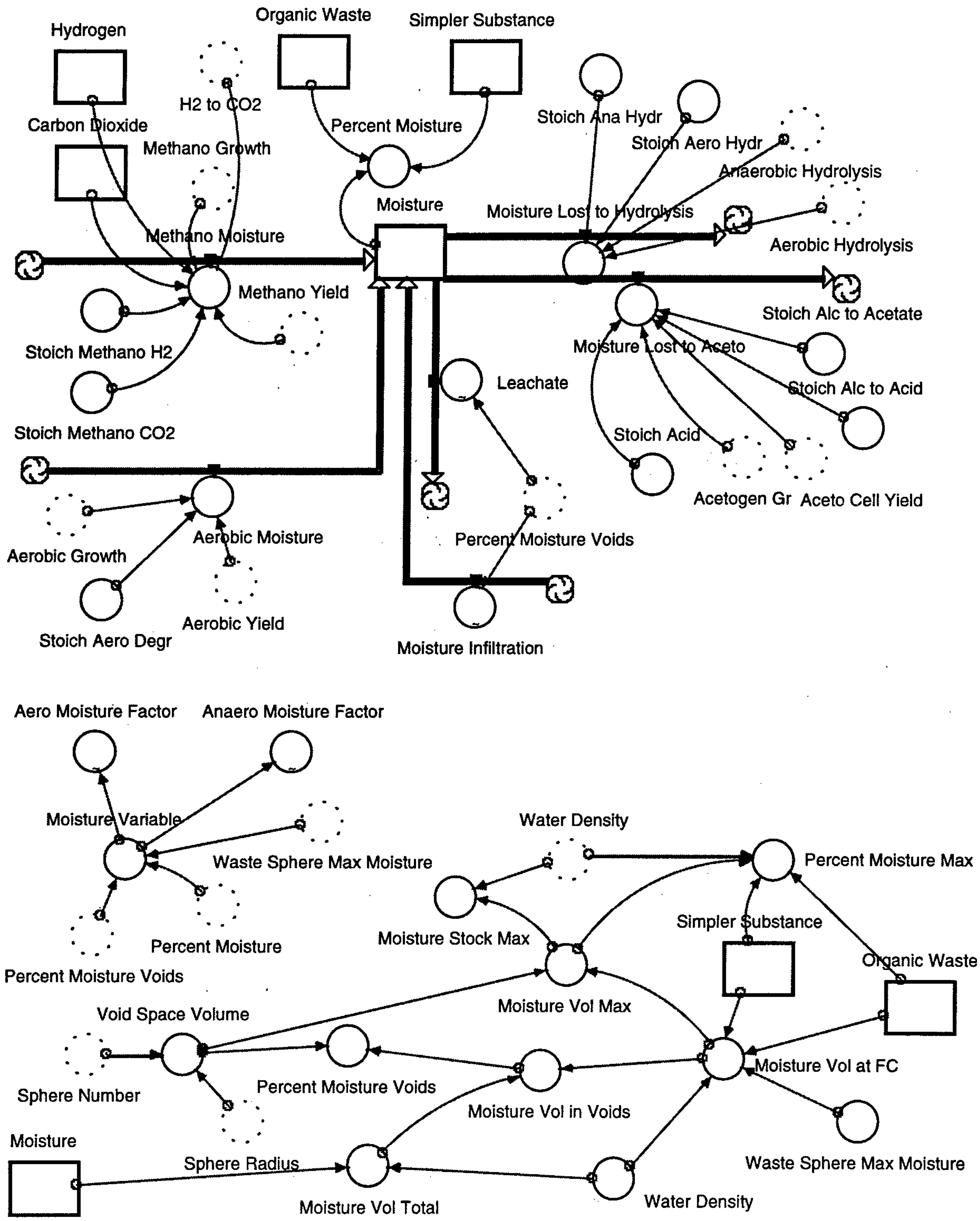
Appendix B: Model Structure

Due to the size of the model structure, it is presented over the next five pages.

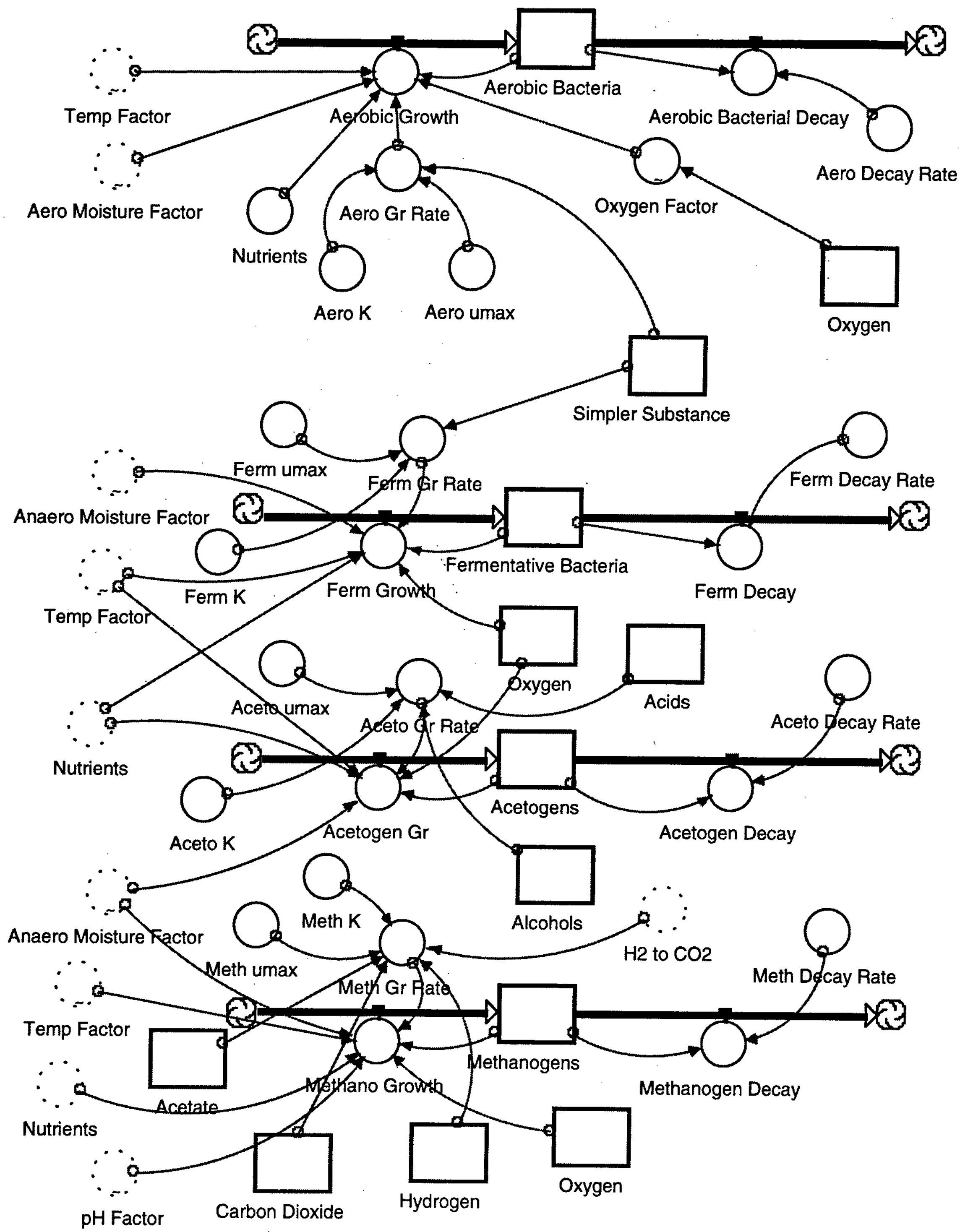
Waste Degradation Sector



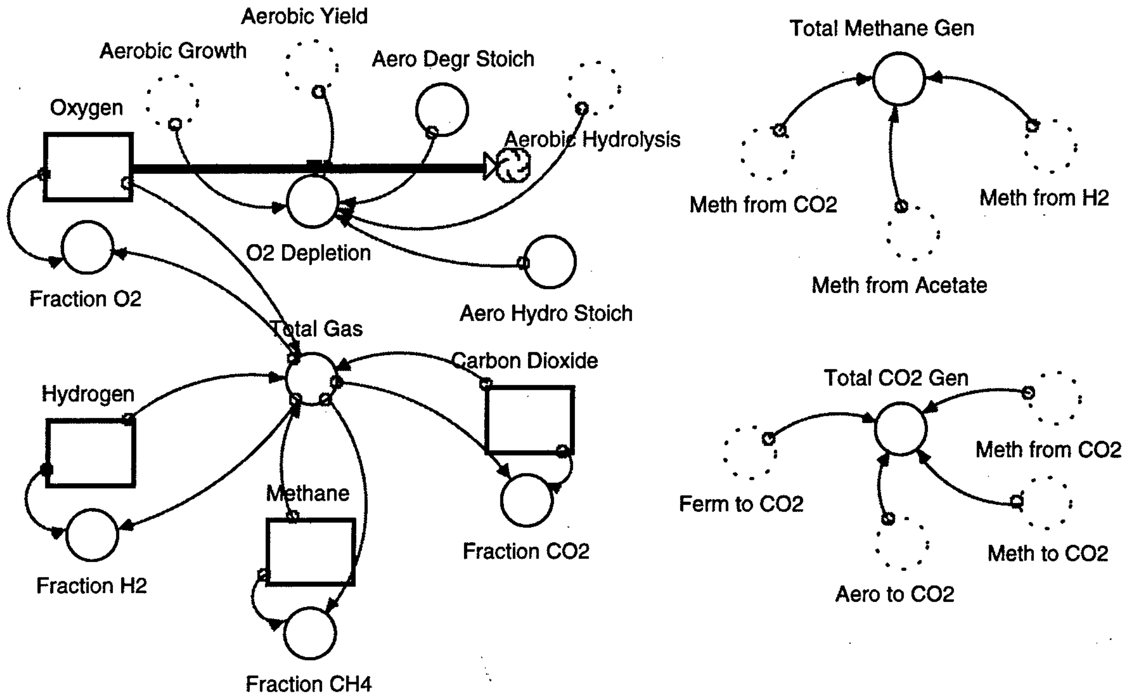
Moisture Sector



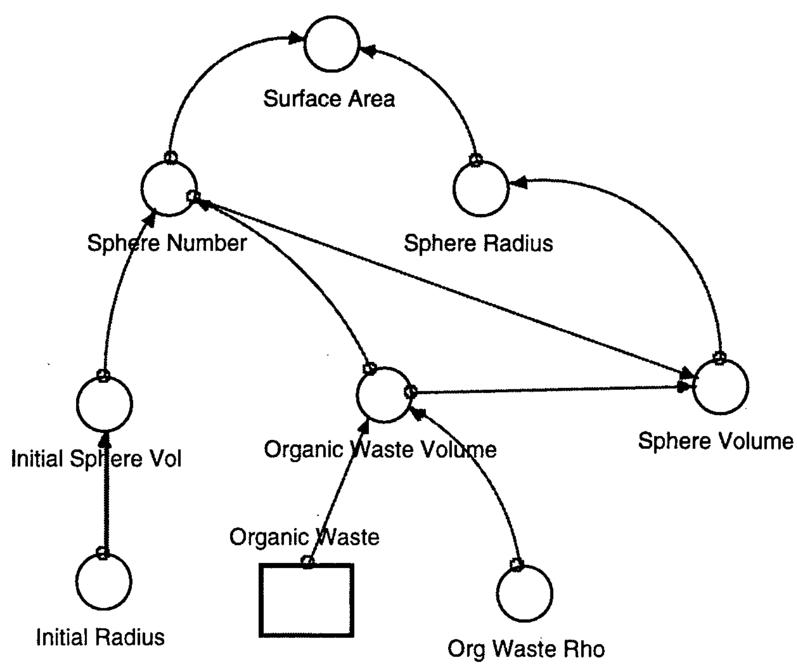
Biomass Sector



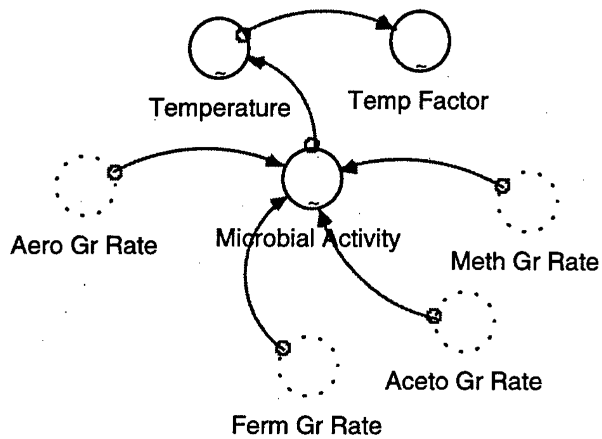
Gas Sector



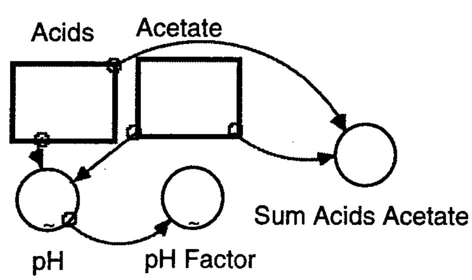
Surface Area Sector



Temperature Sector



pH Sector



Appendix C: Model Equations

Due to the number of model equations, they are presented over the next seven pages.

Biomass Sector

Acetogens(t) = Acetogens(t - dt) + (Acetogen_Gr - Acetogen_Decay) * dt
INIT Acetogens = 100
INFLOWS:
Acetogen_Gr =
IF(Oxygen=0)AND(Nutrients=1)THEN(Acetogens*(Aceto_Gr_Rate*Anaero_Moisture_Factor*Temp_Factor))ELSE(0)
OUTFLOWS:
Acetogen_Decay = Acetogens*Aceto_Decay_Rate

Aerobic_Bacteria(t) = Aerobic_Bacteria(t - dt) + (Aerobic_Growth - Aerobic_Bacterial_Decay) * dt
INIT Aerobic_Bacteria = 10000
INFLOWS:
Aerobic_Growth =
IF(Nutrients=1)THEN(Aerobic_Bacteria*(Aero_Gr_Rate*Aero_Moisture_Factor*Temp_Factor*Oxygen_Factor))ELSE(0)
OUTFLOWS:
Aerobic_Bacterial_Decay = Aerobic_Bacteria*Aero_Decay_Rate

Fermentative_Bacteria(t) = Fermentative_Bacteria(t - dt) + (Ferm_Growth - Ferm_Decay) * dt
INIT Fermentative_Bacteria = 1000
INFLOWS:
Ferm_Growth =
IF(Oxygen=0)AND(Nutrients=1)THEN(Fermentative_Bacteria*(Ferm_Gr_Rate*Anaero_Moisture_Factor*Temp_Factor))ELSE(0)
OUTFLOWS:
Ferm_Decay = Fermentative_Bacteria*Ferm_Decay_Rate

Methanogens(t) = Methanogens(t - dt) + (Methano_Growth - Methanogen_Decay) * dt
INIT Methanogens = 100
INFLOWS:
Methano_Growth =
IF(Oxygen=0)AND(Nutrients=1)THEN(Methanogens*(Meth_Gr_Rate*Anaero_Moisture_Factor*Temp_Factor*pH_Factor))ELSE(0)
OUTFLOWS:
Methanogen_Decay = Methanogens*Meth_Decay_Rate

Aceto_Decay_Rate = .1
Aceto_Gr_Rate =
MAX(Aceto_umax*((Acids)/(Aceto_K+Acids)),Aceto_umax*((Alcohols)/(Aceto_K+Alcohols)))
Aceto_K = 750

Aceto_umax = .55
Aero_Decay_Rate = .1
Aero_Gr_Rate = ((Aero_umax*Simpler_Substance)/(Aero_K+Simpler_Substance))
Aero_K = 50
Aero_umax = 1
Ferm_Decay_Rate = .1
Ferm_Gr_Rate = ((Ferm_umax*Simpler_Substance)/(Ferm_K+Simpler_Substance))
Ferm_K = 500
Ferm_umax = .6
Meth_Decay_Rate = .01
Meth_Gr_Rate =
IF((H2_to_CO2<.18)AND(Hydrogen>0)AND(Acetate>0))THEN(MAX((Meth_umax*Carbon_Dioxide*Hydrogen)/((Meth_K+Carbon_Dioxide)*(Meth_K+Hydrogen)),((Meth_umax*Acetate)/(Meth_K+Acetate))))ELSE((Meth_umax*Acetate)/(Meth_K+Acetate))
Meth_K = 1000
Meth_umax = .525
Nutrients = 1
Oxygen_Factor = GRAPH(Oxygen)
(0.00, 0.00), (10.0, 0.085), (20.0, 0.205), (30.0, 0.295), (40.0, 0.41), (50.0, 0.495), (60.0, 0.615), (70.0, 0.705), (80.0, 0.795), (90.0, 0.905), (100, 0.995)

Gas Sector

Oxygen(t) = Oxygen(t - dt) + (- O2_Depletion) * dt
INIT Oxygen = 100000000
OUTFLOWS:
O2_Depletion =
(Aerobic_Hydrolysis*Aero_Hydro_Stoich)+(Aerobic_Growth*(1/Aerobic_Yield)*Aero_Degr_Stoich)

Aero_Degr_Stoich = 1.2
Aero_Hydro_Stoich = 9.2
Fraction_CH4 = Methane/Total_Gas
Fraction_CO2 = Carbon_Dioxide/Total_Gas
Fraction_H2 = Hydrogen/Total_Gas
Fraction_O2 = Oxygen/Total_Gas
Total_CO2_Gen = (Aero_to_CO2+Ferm_to_CO2+Meth_to_CO2)-Meth_from_CO2
Total_Gas = Oxygen+Carbon_Dioxide+Hydrogen+Methane
Total_Methane_Gen = Meth_from_Acetate+Meth_from_CO2+Meth_from_H2

Moisture Sector

Moisture(t) = Moisture(t - dt) + (Aerobic_Moisture + Methano_Moisture + Moisture_Infiltration - Moisture_Lost_to_Hydrolysis - Moisture_Lost_to_Aceto - Leachate) * dt
INIT Moisture = 340000000
INFLOWS:
Aerobic_Moisture = Aerobic_Growth*(1/Aerobic_Yield)*Stoich_Aero_Degr
Methano_Moisture =
IF(H2_to_CO2<.18)AND(Hydrogen>=8)AND(Carbon_Dioxide>=44)THEN((Methano_Growth*(1/Methano_Yield)*Stoich_Methano_H2)+(Methano_Growth*(1/Methano_Yield)*Stoich_Methano_CO2))ELSE(0)
Moisture_Infiltration = GRAPH(Percent_Moisture_Voids)
(0.00, 1e+007), (10.0, 9e+006), (20.0, 8e+006), (30.0, 7e+006), (40.0, 6e+006), (50.0, 5e+006), (60.0, 4e+006), (70.0, 3e+006), (80.0, 2e+006), (90.0, 0.00), (100, 0.00)
OUTFLOWS:
Moisture_Lost_to_Hydrolysis =
Aerobic_Hydrolysis*Stoich_Aero_Hydr+Anaerobic_Hydrolysis*Stoich_Ana_Hydr
Moisture_Lost_to_Aceto =
(Stoich_Acid*Acetogen_Gr*(1/Aceto_Cell_Yield))+(Stoich_Alc_to_Acetate*Acetogen_Gr*(1/Aceto_Cell_Yield))+(Stoich_Alc_to_Acid*Acetogen_Gr*(1/Aceto_Cell_Yield))
Leachate = GRAPH(Percent_Moisture_Voids)
(0.00, 0.00), (10.0, 250000), (20.0, 500000), (30.0, 750000), (40.0, 1e+006), (50.0, 1.3e+006), (60.0, 1.5e+006), (70.0, 1.8e+006), (80.0, 2e+006), (90.0, 2.3e+006), (100, 2.5e+006)
Moisture_Stock_Max = Moisture_Vol_Max*Water_Density
Moisture_Variable = IF(Percent_Moisture<Waste_Sphere_Max_Moisture) THEN((1-(Percent_Moisture/Waste_Sphere_Max_Moisture))*100)
ELSE(Percent_Moisture_Voids)
Moisture_Vol_at_FC = ((Waste_Sphere_Max_Moisture/(100-Waste_Sphere_Max_Moisture))*(Organic_Waste+Simpler_Substance))/Water_Density
Moisture_Vol_in_Voids = IF(Moisture_Vol_Total-Moisture_Vol_at_FC<0) THEN(0)
ELSE(Moisture_Vol_Total-Moisture_Vol_at_FC)
Moisture_Vol_Max = Void_Space_Volume+Moisture_Vol_at_FC
Moisture_Vol_Total = Moisture/Water_Density
Percent_Moisture = (Moisture/(Organic_Waste+Simpler_Substance+Moisture))*100
Percent_Moisture_Max =
((Moisture_Vol_Max*Water_Density)/(Organic_Waste+Simpler_Substance+(Moisture_Vol_Max*Water_Density)))*100
Percent_Moisture_Voids = MIN((Moisture_Vol_in_Voids/Void_Space_Volume)*100, 100)
Stoich_Acid = .49
Stoich_Aero_Degr = .6
Stoich_Aero_Hydr = .1
Stoich_Alc_to_Acetate = .39
Stoich_Alc_to_Acid = .3

Stoich_Ana_Hydr = .04
Stoich_Methano_CO2 = .82
Stoich_Methano_H2 = 4.5
Void_Space_Volume = (((2*Sphere_Radius)^3)-(4/3*PI*Sphere_Radius^3))*Sphere_Number
Waste_Sphere_Max_Moisture = 35
Water_Density = 1000
Aero_Moisture_Factor = GRAPH(Moisture_Variable)
(-100, 0.00), (-90.0, 0.04), (-80.0, 0.08), (-70.0, 0.12), (-60.0, 0.16), (-50.0, 0.2), (-40.0, 0.24), (-30.0, 0.28), (-20.0, 0.32), (-10.0, 0.36), (0.00, 0.4), (10.0, 0.5), (20.0, 0.63), (30.0, 0.77), (40.0, 0.905), (50.0, 1.00), (60.0, 1.00), (70.0, 0.955), (80.0, 0.845), (90.0, 0.7), (100, 0.5)
Anaero_Moisture_Factor = GRAPH(Moisture_Variable)
(-100, 0.00), (-90.0, 0.04), (-80.0, 0.08), (-70.0, 0.12), (-60.0, 0.16), (-50.0, 0.2), (-40.0, 0.24), (-30.0, 0.28), (-20.0, 0.32), (-10.0, 0.36), (0.00, 0.4), (10.0, 0.48), (20.0, 0.59), (30.0, 0.7), (40.0, 0.8), (50.0, 0.85), (60.0, 0.9), (70.0, 0.93), (80.0, 0.96), (90.0, 0.98), (100, 1.00)

pH Sector

Sum Acids Acetate = Acetate+Acids
pH = GRAPH(Acids+Acetate)
(0.00, 7.80), (1e+011, 7.70), (2e+011, 7.60), (3e+011, 7.50), (4e+011, 7.40), (5e+011, 7.20), (6e+011, 7.00), (7e+011, 6.80), (8e+011, 6.60), (9e+011, 6.50), (1e+012, 6.45)
pH_Factor = GRAPH(pH)
(4.00, 0.00), (4.40, 0.00), (4.80, 0.00), (5.20, 0.00), (5.60, 0.00), (6.00, 0.1), (6.40, 1.00), (6.80, 1.00), (7.20, 1.00), (7.60, 0.96), (8.00, 0.00)

Surface Area Sector

Initial_Radius = .07
Initial_Sphere_Vol = (4*PI*Initial_Radius^3)/3
Organic_Waste_Volume = Organic_Waste/Org_Waste_Rho
Org_Waste_Rho = 1352.61
Sphere_Number = INIT(Organic_Waste_Volume)/(Initial_Sphere_Vol)
Sphere_Radius = (3*Sphere_Volume/(4*PI))^(1/3)
Sphere_Volume = Organic_Waste_Volume/Sphere_Number
Surface_Area = Sphere_Number*4*PI*Sphere_Radius*Sphere_Radius

Temperature Sector

Microbial_Activity =
GRAPH(Aero_Gr_Rate+Aceto_Gr_Rate+Ferm_Gr_Rate+Meth_Gr_Rate)
(0.00, 0.00), (0.35, 0.0438), (0.7, 0.0688), (1.05, 0.106), (1.40, 0.156), (1.75, 0.206), (2.10, 0.3), (2.45, 0.4), (2.80, 0.575), (3.15, 0.775), (3.50, 1.25)
Temperature = GRAPH(Microbial_Activity)
(0.00, 20.0), (0.125, 32.6), (0.25, 40.4), (0.375, 43.8), (0.5, 46.4), (0.625, 49.0), (0.75, 51.4), (0.875, 53.2), (1.00, 55.6), (1.13, 57.6), (1.25, 60.0)
Temp_Factor = GRAPH(Temperature)
(0.00, 0.00), (6.00, 0.025), (12.0, 0.08), (18.0, 0.24), (24.0, 0.61), (30.0, 0.89), (36.0, 1.00), (42.0, 1.00), (48.0, 1.00), (54.0, 0.905), (60.0, 0.005)

Waste Degradation Sector

Acetate(t) = Acetate(t - dt) + (Aceto_from_Acids + Aceto_from_Alc + Ferm_to_Acetate - Meth_from_Acetate - Meth_to_CO2) * dt
INIT Acetate = 0
INFLOWS:
Aceto_from_Acids = Acetogen_Gr*(1/Aceto_Cell_Yield)*Aceto_from_Acid_Stoich
Aceto_from_Alc = Acetogen_Gr*(1/Aceto_Cell_Yield)*Aceto_from_Alc_Stoich
Ferm_to_Acetate = Ferm_Growth*(1/Ferm_Cell_Yield)*Ferm_to_Acetate_Stoich
OUTFLOWS:
Meth_from_Acetate =
Methano_Growth*(1/Methano_Yield)*Methano_from_Acetate_Stoich
Meth_to_CO2 = Methano_Growth*(1/Methano_Yield)*Methano_to_CO2_Stoich

Acids(t) = Acids(t - dt) + (Ferm_to_Acids + Aceto_to_Acid - Aceto_to_H2n - Aceto_from_Acids) * dt
INIT Acids = 0
INFLOWS:
Ferm_to_Acids = Ferm_Growth*(1/Ferm_Cell_Yield)*Ferm_to_Acid_Stoich
Aceto_to_Acid = Acetogen_Gr*(1/Aceto_Cell_Yield)*Aceto_to_Acid_Stoich
OUTFLOWS:
Aceto_to_H2n = Acetogen_Gr*(1/Aceto_Cell_Yield)*Aceto_to_H2_Stoich
Aceto_from_Acids = Acetogen_Gr*(1/Aceto_Cell_Yield)*Aceto_from_Acid_Stoich

Alcohols(t) = Alcohols(t - dt) + (Ferm_to_Alc - Aceto_to_Acid - Aceto_from_Alc - Aceto_to_H2_from_Alc) * dt
INIT Alcohols = 0
INFLOWS:
Ferm_to_Alc = Ferm_Growth*(1/Ferm_Cell_Yield)*Ferm_to_Alc_Stoich
OUTFLOWS:
Aceto_to_Acid = Acetogen_Gr*(1/Aceto_Cell_Yield)*Aceto_to_Acid_Stoich
Aceto_from_Alc = Acetogen_Gr*(1/Aceto_Cell_Yield)*Aceto_from_Alc_Stoich

Aceto_to_H2_from_Alc =
Acetogen_Gr*(1/Aceto_Cell_Yield)*Aceto_to_H2_from_Alc_Stoich

Carbon_Dioxide(t) = Carbon_Dioxide(t - dt) + (Ferm_to_CO2 + Aero_to_CO2 + Meth_to_CO2 - Meth_from_CO2) * dt
INIT Carbon_Dioxide = 0
INFLOWS:
Ferm_to_CO2 = Ferm_Growth*(1/Ferm_Cell_Yield)*Ferm_to_CO2_Stoich
Aero_to_CO2 = Aerobic_Growth*(1/Aerobic_Yield)*Degradation_Stoich
Meth_to_CO2 = Methano_Growth*(1/Methano_Yield)*Methano_to_CO2_Stoich
OUTFLOWS:
Meth_from_CO2 =
IF((H2_to_CO2<.18)AND(Carbon_Dioxide>=44))THEN(Methanogenesis*Methano_from_CO2_Stoich)ELSE(0)

Hydrogen(t) = Hydrogen(t - dt) + (Ferm_to_H2 + Aceto_to_H2n + Aceto_to_H2_from_Alc - Meth_from_H2) * dt
INIT Hydrogen = 0
INFLOWS:
Ferm_to_H2 = Ferm_Growth*(1/Ferm_Cell_Yield)*Ferm_to_H2_Stoich
Aceto_to_H2n = Acetogen_Gr*(1/Aceto_Cell_Yield)*Aceto_to_H2_Stoich
Aceto_to_H2_from_Alc =
Acetogen_Gr*(1/Aceto_Cell_Yield)*Aceto_to_H2_from_Alc_Stoich
OUTFLOWS:
Meth_from_H2 =
IF((H2_to_CO2<.18)AND(Hydrogen>=8))THEN(Methanogenesis*Methano_from_H2_Stoich)ELSE(0)

Methane(t) = Methane(t - dt) + (Meth_from_CO2 + Meth_from_H2 + Meth_from_Acetate) * dt
INIT Methane = 0
INFLOWS:
Meth_from_CO2 =
IF((H2_to_CO2<.18)AND(Carbon_Dioxide>=44))THEN(Methanogenesis*Methano_from_CO2_Stoich)ELSE(0)
Meth_from_H2 =
IF((H2_to_CO2<.18)AND(Hydrogen>=8))THEN(Methanogenesis*Methano_from_H2_Stoich)ELSE(0)
Meth_from_Acetate =
Methano_Growth*(1/Methano_Yield)*Methano_from_Acetate_Stoich

Organic_Waste(t) = Organic_Waste(t - dt) + (- Aerobic_Hydrolysis - Anaerobic_Hydrolysis) * dt
INIT Organic_Waste = 1000000000
OUTFLOWS:

```
Aerobic_Hydrolysis =
Aero_Depletion*Surface_Area*Aero_Moisture_Factor*Temp_Factor*Oxygen_Factor
Anaerobic_Hydrolysis =
Anaero_Depletion*Surface_Area*Anaero_Moisture_Factor*Temp_Factor

Simpler_Substance(t) = Simpler_Substance(t - dt) + (Aerobic_Hydrolysis +
Anaerobic_Hydrolysis - Ferm_to_CO2 - Aero_to_CO2 - Ferm_to_H2 - Ferm_to_Acids -
Ferm_to_Alc - Ferm_to_Acetate) * dt
INIT Simpler_Substance = 0
INFLOWS:
Aerobic_Hydrolysis =
Aero_Depletion*Surface_Area*Aero_Moisture_Factor*Temp_Factor*Oxygen_Factor
Anaerobic_Hydrolysis =
Anaero_Depletion*Surface_Area*Anaero_Moisture_Factor*Temp_Factor
OUTFLOWS:
Ferm_to_CO2 = Ferm_Growth*(1/Ferm_Cell_Yield)*Ferm_to_CO2_Stoich
Aero_to_CO2 = Aerobic_Growth*(1/Aerobic_Yield)*Degradation_Stoich
Ferm_to_H2 = Ferm_Growth*(1/Ferm_Cell_Yield)*Ferm_to_H2_Stoich
Ferm_to_Acids = Ferm_Growth*(1/Ferm_Cell_Yield)*Ferm_to_Acid_Stoich
Ferm_to_Alc = Ferm_Growth*(1/Ferm_Cell_Yield)*Ferm_to_Alc_Stoich
Ferm_to_Acetate = Ferm_Growth*(1/Ferm_Cell_Yield)*Ferm_to_Acetate_Stoich

Aceto_Cell_Yield = .4
Aceto_from_Acid_Stoich = 1.2
Aceto_from_Alc_Stoich = 1.3
Aceto_to_Acid_Stoich = 1.2
Aceto_to_H2_from_Alc_Stoich = .09
Aceto_to_H2_Stoich = .03
Aerobic_Yield = .6
Aero_Depletion = 2.43
Anaero_Depletion = Aero_Depletion/10000
Degradation_Stoich = 1.5
Ferm_Cell_Yield = .5
Ferm_to_Acetate_Stoich = .3
Ferm_to_Acid_Stoich = .3
Ferm_to_Alc_Stoich = .2
Ferm_to_CO2_Stoich = .19
Ferm_to_H2_Stoich = .009
H2_to_CO2 = IF(Carbon_Dioxide>0)THEN (Hydrogen/Carbon_Dioxide) ELSE (0.18)
Methanogenesis = Methano_Growth*(1/Methano_Yield)
Methano_from_Acetate_Stoich = .3
Methano_from_CO2_Stoich = .4
Methano_from_H2_Stoich = 2
Methano_to_CO2_Stoich = .7
Methano_Yield = .4
```

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ABSTRACT (*Maximum 200 Words*)

Solid waste landfills are an extremely complex and heterogeneous environment. Modeling the biodegradation processes within a landfill must involve an understanding of how environmental factors affect these processes. Arguably, the most important environmental factor influencing biodegradation processes is solid waste moisture content.

This research effort, which is an extension of a system dynamics model previously presented by Colborn (1997) and amended by Benter (1999), attempts to understand and model the effects of moisture content on waste degradation and landfill gas generation. The new moisture structure that was added to the previous models provides a better representation of the impact of moisture on aerobic and anaerobic hydrolysis and bacterial populations, and ultimately, gas generation. It also gives a clearer picture of how moisture is distributed between the solid waste and the void spaces within a landfill. Leachate and moisture infiltration flows were introduced into the model as a means to replicate the "wet-cell" or bioreactor landfill. Landfill managers could change the moisture parameters in the model to simulate the impact of different moisture configurations on waste degradation and methane generation. Transferring the information learned from the model to a real system could help optimize methane generation and accelerate landfill stabilization.

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